AIRS TEAM SCIENCE DATA VALIDATION PLAN

Core Products

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1.0 Introduction

1.1 AIRS/AMSU-A/HSB Measurement Goals

The Earth's climate is a complex system with many components and feedback processes that operate on different time scales. The slow components involve the deep oceans, and permanent and semi-permanent ice and snow covers. Their response sets the pace for long-term climate trends and may introduce a delay of 50 years or more in the response of the climate system to external forcing. The fast components, whose scales range from hours to multiple seasons, encompass the atmosphere, upper ocean layers, and include the biosphere as well as air-land and air-sea interactions. The fast components are coupled to are controlled by the atmosphere, which drives the whole Earth environment and determines the amplitude and geographical patterns of climate change. The atmosphere controls many feedback processes that involve the interaction of radiation with clouds, water vapor, precipitation and temperature. Thus, a knowledge of the properties of the atmosphere is important not only for understanding processes that occur within the atmosphere itself; but also for understanding the feedback mechanisms among the various components of the entire climate system. Atmospheric and surface measurements from the Atmospheric InfraRed Sounder (AIRS), Advanced Microwave Sounding Unit (AMSU-A) and the Humidity Sounder for Brazil (HSB) will provide data about these interactions with unprecedented accuracy.

The ability of AIRS/AMSU-A/HSB to provide simultaneous observations of the Earth's atmospheric temperature, ocean surface temperature, and land surface temperature, as well as humidity, clouds, albedo, and the distribution of greenhouse gases, makes AIRS the primary Earth Observing System (EOS) instrument for investigating several interdisciplinary issues to be addressed in Earth science. Among these issues are:

- Improving numerical weather prediction.
- Demonstrating seasonal to interannual predictions of the effects of El Nino and other transient climate anomalies.
- Characterizing the optical properties of atmospheric constituents, cloud and aerosols, in order to compute radiation fluxes.
- Monitoring variations and trends in the global energy and water cycles.

1.2 Mission

AIRS/AMSU-A/HSB is planned for launch in 2000 on the EOS PM-1 platform. It will be placed into a polar, sun-synchronous orbit with a nominal altitude of 705 km and an inclination of 98.2° and an orbital period of 98.8 minutes. The repeat cycle is 233 orbits (16 days) with a ground track repeatability of ±20 km. The platform will have an equatorial crossing time of 1:30 PM. The payload on the EOS PM-1 will include the AIRS/AMSU-A/HSB, Moderate Resolution Imaging Spectroradiometer (MODIS), Clouds and Earth's Radiant Energy System (CERES), and Advanced Microwave Scanning Radiometer (AMSR).

1.3 AIRS Core Data Products

The AIRS team has made a distinction between ready-at-launch core products “standard products” and ready after launch products “research products”. Only the Standard AIRS/AMSU-A/HSB science data products will be discussed in this document.

<u>Radiance Measurements, Level 1 Products</u>

AIR02 : Level 1-B Radiance, AIRS
Calibrated, time-tagged and geolocated AIRS instrument radiances

AMS02: Level 1-B Radiance, AMSU-A
Calibrated, time-tagged and geolocated AMSU-A instrument radiances

MHS02: Level 1-B Radiance, HSB
Calibrated, time-tagged and geolocated HSB instrument radiances

<u>Derived Geophysical Products, Level 2 Products</u>

AIR04: Cloud Product
The core products consist of cloud cover, cloud height, cloud top temperature and cloud emissivity at four selected infrared wavelength bands. The spatial resolution of these products is on the AIRS individual field of view, or 13.5 km at nadir.

AIR05: Humidity Product
The humidity products include the humidity profile at 2 km layers in the troposphere and the integrated total amount of water vapor. The spatial resolution of the humidity products is on the AMSU-A footprint, roughly 40 km at nadir.

AIR07: Temperature Product
The temperature products include the temperature profile at 1 km levels in the troposphere, sea surface temperature, land surface temperature and its associated land surface emissivity, and a day minus night surface temperature. The spatial resolution of the temperature products is on the AMSU-A footprint or roughly 40 km at nadir.

AIR08: Ozone Product
The ozone product is the total column amount of ozone at a spatial resolution of 45 km at nadir.

AIR09: Radiance, Cloud-cleared
The cloud-cleared radiance product is produced at a resolution of the AMSU-A footprint, or 40 km at nadir.

1.4 Validation Goals

There are two distinct phases to the validation effort: pre-launch and post-launch. The goals of the pre-launch and post-launch activities are outlined in Tables 1.1 and 1.2.

Table 1.1: Pre-launch Goals

1. Spectroscopic validation
2. Forward Model validation
3. Infrared and visible spectral information about clouds/homogeneous land surfaces; development of a spectral catalogue
4. Land surface inhomogeneity effects
5. Algorithm/data system verification and error analysis

Table 1.2: Post-launch Goals

1. Standard Product validation
2. Absolute calibration for the visible channels
3. Spectroscopic validation
4. Forward Model Validation

Spectroscopic validation refers to the molecular physics that goes into a line-by-line transmittance/radiance algorithm. Spectroscopic validation includes (a) laboratory measurements and analysis of spectra that are not sufficiently well known for AIRS applications, (b) field measurements of atmospheric spectra that cannot be adequately characterized in the laboratory (generally due to insufficient optical depths in the lab) and will be used to improve spectroscopic models, and (c) field measurements of atmospheric spectra to validate our existing spectroscopic models in the real atmosphere. (b) and (c) are related, but (b) is much more demanding in that we assume that in-situ measurements of the atmospheric state are more accurate than the spectroscopy we are trying to measure.

Forward model validation tests (a) the fast parametrization of the spectroscopy in the form of the fast transmittance algorithm, (b) the fast radiance algorithm that uses these fast transmittances, (c) the instrument spectral response function used in (a), and (d) the computer codes used in a-c. The AIRS Radiative Transfer Validation Model (RTVM) is the link between line-by-line codes and the fast forward radiance model.

Development of a spectral catalogue for clouds and surfaces and the study of surface inhomogeneity effects are critical to accurately understanding the physics and hence the radiative transfer modeling and thus improving the accuracy of the products.

1.5 Document Summary

This document describes three components of the AIRS/AMSU-A/HSB validation of core products:

1. Team Leader/Team Member participation funded through existing TL/TM budgets (sections 3.2, 3.4, 3.5, 3.6, 4.3, 4.4 and 5)
2. Pre-flight instrument performance validation funded through the EOS Project Scientist (section 3.7)
3. Validation campaign activities funded through the EOS Validation Office (3.1, 3.3, 4.1, 4.2)

Specific product validation is mentioned throughout the document. The retrieval of geophysical products from AIRS/AMSU-A/HSB measurements is done in a simultaneous fashion. Because of this, the products are self-consistent and match the outgoing radiances observed by the instruments. This in turn makes the key to the validation process the validation of the temperature product (AIR07) as described in section 4.3.2 and 4.4. Land and Sea Surface Temperature validation are described in sections 4.1 and 4.3.

Water vapor (AIR05) validation is described in the same sections (4.3.2 and 4.4) as are special needs because of its higher spatial and temporal variation. Special radiosonde campaigns are being planned with a finer space and time resolution.

Ozone (AIR08) is described in sections 4.3.2 and 4.3.3 dealing with ozonesondes and cross validation with other space-borne sensors.

The cloud product (AIR04) validation is described in the cross validation section 4.3.3.

The radiances (AIR02, AMS02, MHS02, and AIR09) are described in 2.1.4, 3.1, 3.3, 4.3.3 (VIS only).

Many of the aspects of the validation activities planned for AIRS apply equally for AMSU-A and HSB. Microwave-specific aspects are only described when it is necessary to make a distinction.

AIRS Calibration / Validation

Lockheed/Martin Responsibility

	PARAMETER	MEASUREMENT APPROACH	CALIBRATION	INSTRUMENT PERFORMANCE VALIDATION
1	Scene Dynamic Range	Sweep LABB over dynamic range	Demonstrated FRD compliance	
	Radiometric Calibration Accuracy	Same test as above	FRD compliance proven by analysis	Curve fit for non-linearity correction
2	Scan Response Uniformity	LABB at 300K and 250K all angles from ±50 degrees	Demonstrated FRD compliance	need two temperatures at all angles from ±50 degrees to validate polarization correction algorithm Validate that NEN is not scan angle dependent
3	Sensitivity (NEΔT)	LABB at 220K, 250K, 300K and 340K	Characterize rms noise at full dynamic range. Characterize 1/f noise (if any)	Indirect validation during the 24 hour test.
4	Spectral Coverage	FT-Interferometer	Acceptance test to demonstrated FRD compliance	
	FWHM @ 14µm Width at 50% of area Width at 95% of area Area outside λ± 6 Δλ	Same test as above	Characterizes SRF at all wavelength with more than 1/3000 of peak response	Evaluate retrieval error if not FRD compliant Validate grating model for spectral calibration Validate non-linearity correction based on ghost suppression
	SRF centered knowledge	same test as above		
5	Wavelength Calibration stability in 24 hours	24 hours test with gas-cell at nadir position		Validate spectral calibration algorithm. validate frequency tracking algorithm
6	Spatial Response IFOV FWHM 99% of power 99.5% of power	<0.5 degree pointsource in azimuth and elevation		
7	Measurement Simultaneity	<0.5 degree point source rasterscan in 1.5 degree diameter field	Calculate Cij from spatial response test	
8	Instrumental Polarization	Rotate infrared polarizer between a black-body source	Measure polarization angle and principal axis at all wavelengths	Validate polarization correction equation
9	spectral centered and resolution absolute calibration	variable pressure gas cell		compare with calculated gas absorption depth and positions
10	end-to-end pre-launch system test	Vertical look through earth atmosphere at night and day		compare with uplooking AERI interferometer compare with lfast-code

AIRS Science Team Responsibility

PRODUCT VALIDATION	Task	PreLaunch	PostLaunch
1	Spectroscopic Validation	Laboratory Work, Field Campaigns (intermittent)	Laboratory Work, Field Campaigns (intermittent)
2	Forward Model Validation	Improve the physics and field test results	Field Campaigns (intermittent)
3	Field Campaign Studies	Data set preparation, development of plans, instrument monitoring	Data set preparation, development of plans, instrument monitoring
4	Long term Intercomparison	Code development	Radiosonde collocation and analysis. (long term)
5	Algorithm Error Characterization	Simulation system development	Maintenance
6	Radiance validation	Code development	Long term trend monitoring, Vicarious radiance validation (intermittent). Cross validation with other instruments. (intermittent)
7	Geophysical parameter validation	Assess error characteristics of InSitu data sources	InSitu assessment, cross validation with other instruments, model verification (long term)
8	Model Assimilation	Development of AIRS specific assimilation	Impact assessment of AIRS data
9	Validation Data System Development	Data Warehouse development, analysis software development	Maintenance

2.0 Validation Approach

The validation strategy of AIRS is based on four major components:

- Short-term field campaigns
- Long-term parameter monitoring such as radiosondes
- Long-term statistical analysis of means, variances, trends, etc.
- Verification through the use of AIRS data in assimilation models

Sustaining Validation Efforts	**Intermittent Validation efforts**
Radiosondes	Field campaigns
Surface data	Forward problem validation
Cross-instrument validation	Radiance validation Special atmospheric and surface conditions
Comparison of assimilation and analysis products with AIRS products	Ongoing activities (e.g., GEWEX)

2.1 Instrument and Mathematical Description

2.1.1 Instrument Model

2.1.1a AIRS IR

AIRS is a continuously operating cross-track scanning sounder, consisting of a telescope that feeds an echelle spectrometer. The spectrometer analyzes thermal infrared radiation between the wavenumbers of 650 cm^{-1} - 2700 cm^{-1}, with an average resolving power of 1200. This spectral region includes the important temperature sounding regions in the 4.2 and 15µm CO_2 bands, water vapor sounding in the 6.3 µm water band and ozone sounding in the 9.6 µm region. AIRS has about 2400 detector elements at the focal plane, arranged in several linear arrays. Each detector has a noise-equivalent difference temperature on the order of 0.2K (at 250K) seen in each 1.1° Instantaneous Field Of View (IFOV) -- see Figure 2.1.

During each scan, the rotating external mirror scans the underlying Earth from 49° on one side of the nadir to 49° on the other side, in 90 integration periods, and provides two views of dark space, one view of an internal radiometric calibration target, and one view of an internal spectral calibration target. Thus each scan produces 94 sets of measurements (90 Earth scenes and 4 calibrations). The scan is repeated every 8/3 seconds. The downlink data rate from the AIRS instrument is 1.2 Mbit/sec.

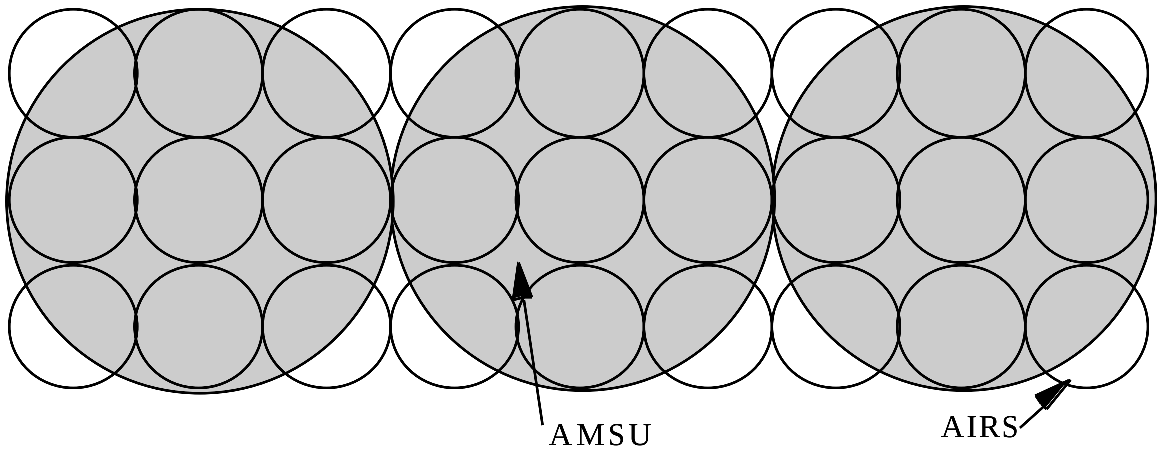


FIGURE 2.1 AIRS/AMSU-A SCHEMATIC FOOTPRINT PATTERN

Radiometric Calibration

The AIRS Functional Requirements Document (FRD) calls for an absolute radiometric instrument calibration accuracy of 3% of the signal or four times the noise-equivalent radiance (NeN), whichever is larger, over the full range of expected effective target brightness temperatures (220 K to 350 K), and the full wavelength range covered by AIRS. This accuracy is to be maintained during five years in orbit.

In an ideal radiometer, incoming radiances and detector output readings are related through the calibration equation

$$N_{ot} = N_c \frac{V_t - V_s}{V_c - V_s} \tag{2.1}$$

where N_{ot} and N_c are the radiances from the target scene and the calibration blackbody, respectively, and V_t, V_c, and V_s are detector outputs for the target scene, calibration blackbody, and space views, respectively. This equation is often stated as a combined detector/system gain

$$G = \frac{N_c}{V_c - V_s} \tag{2.2}$$

and

$$N_{ot} = G(V_t - V_s). \tag{2.3}$$

In order to meet the AIRS radiometric calibration requirements, the algorithm makes use of four major elements:

1. A linearization algorithm.
2. A zero-radiance-input smoothing algorithm.
3. The first order calibration equation.
4. A polarization correction algorithm.

Details of the linearization procedure, which convert numbers to linearized engineering units are not discussed, but the residual error is part of the calibration error budget. An algorithm potentially needed to account for scan angle dependent scan mirror emissivity is discussed, but is currently not part of the baseline calibration. Scan mirror emissivity variations, in the absence of a correction algorithm, are included in the estimation of calibration error. In the following we discuss instrumental details related to the theoretical basis for these algorithms.

For consistency with HIRS/2 instruments on the NOAA polar-orbiting satellites series we have adopted units of $mW/m^2\ cm^{-1}$ sr for the AIRS level 1b spectral radiances. Each of the nineteen HIRS/2 channels can in fact be synthesized by summing about fifty AIRS channels weighted by the appropriate HIRS/2 spectral response function.

Sources of Radiometric Calibration Errors

There are a number of instrumental effects which make the application of the ideal calibration improper. This presents two choices, each of which impacts the instrument design and/or the pre-launch testing:

1. Design the instrument (by specifying some components) such that the effects are small and can be absorbed in the AIRS absolute radiometric calibration budget.
2. Develop correction terms to the ideal calibration equation. The parameters in the correction terms (such as surface emissivities) must either be measured during pre-launch instrument characterization or must be calculable from in-orbit monitoring of additional components, such as temperature sensors.

Figure 2.2 shows the contribution of the three most important errors in the AIRS radiometric calibration: Blackbody output uncertainty, zero-point-offset error, and gain/offset coupled errors and are residual errors after in-flight calibration procedures are applied. Different errors dominate in different wavelength regions. Based on the current knowledge of the subsystem performance, the first two error sources are adequately handled by first order corrections to the engineering units. The gain/offset coupled error requires a one step recursive correction by the calibration algorithm in spectral radiance domain. The root mean square of the uncorrected or uncorrectable residuals constitutes the absolute calibration error. The AIRS FRD requires that the root mean square of all error is less than four times the noise-equivalent radiance (NeN) over the full range of expected scene conditions.

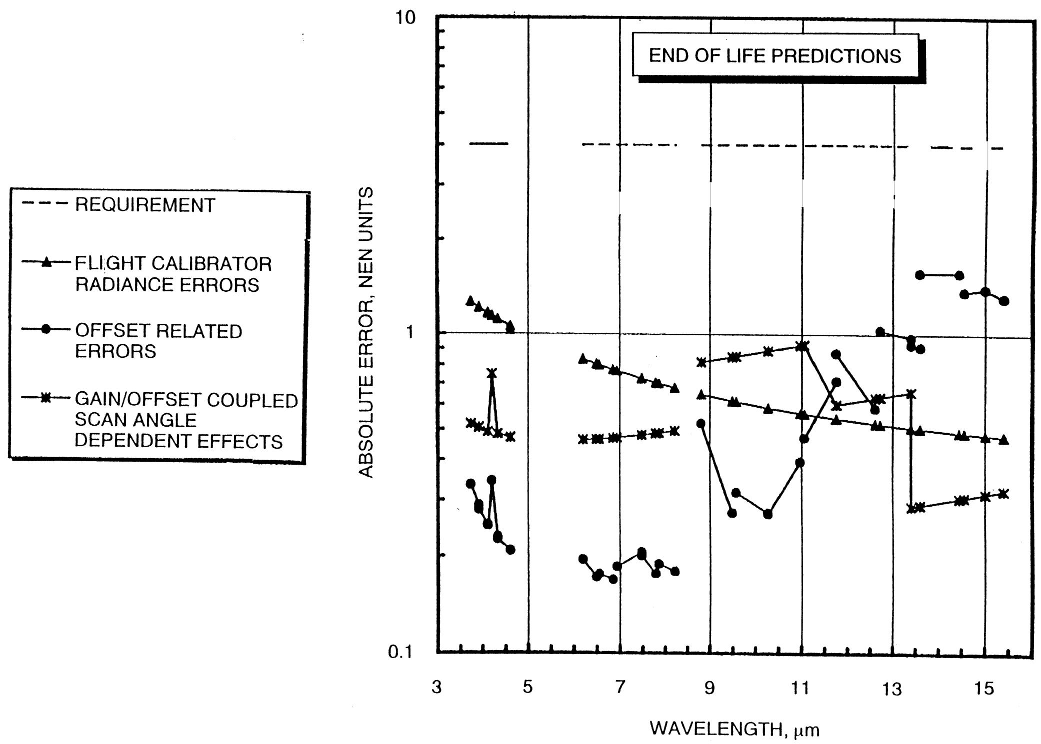


FIGURE 2.2: THE PREDICTED CONTRIBUTION OF THE MOST SIGNIFICANT FACTORS IN THE RADIOMETRIC CALIBRATION UNCERTAINTY. ESTIMATES REFER TO WORST CASE, END-OF- LIFE CONDITIONS. UNDER ALL CONDITIONS THE UNCERTAINTY IS LESS THAN FOUR NEN UNITS.

More details can be found in the AIRS L1B ATBD, Part 1 and in the AIRS Calibration Plan (1997).

2.1.1b AIRS VIS/Near IR

The AIRS instrument carries four visible and near-infrared detectors, hereafter referred to as VIS. Their primary function is to provide diagnostic support to the infrared retrievals: setting flags that warn of the presence of low-clouds or highly variable surface features within the infrared field-of-view. These channels will also aid in integrating AIRS data with data from imaging instruments, such as MODIS. There are also several research products that VIS supports, such as determining cloud physical properties and Earth energy balance studies.

VIS channel 1 covers the range from about 0.4 to 0.44 µm. It is designed to be most sensitive to aerosols. Channels 2 (0.58 to 0.68 µm) and 3 (0.71 to 0.96 µm) approximate the response of AVHRR channels 1 and 2, respectively, and are particularly useful for surface studies. Channel 4 is a broadband filter useful for energy balance studies. It covers the range from about 0.45 to 0.95 µm. Each VIS channel consists of a linear detector array with nine pixels, nominally aligned in the along-track direction. Each pixel has a square field-of-view 0.185 degrees on a side. Projecting this on the nadir point from the nominal 705 km orbit, pixels are 2.28 km wide. For comparison, the AIRS infrared footprint is circular and approximately 13.54 km in diameter. Across-track scanning of the detectors is achieved using the same scan mirror as the IR detectors.

Figure 2.3 indicates the relation between the VIS and infrared footprints, as projected on the ground near nadir. In the figure, the spacecraft flight direction is towards the top of the page, and the three roughly horizontal rows of circles represent three across-track scans of the AIRS and HSB instruments. There are also three across-track scans of a 9 element VIS array, with approximately 1.57 pixels of overlap between VIS scans. (For simplicity, the overlap is drawn as only 1 pixel.)

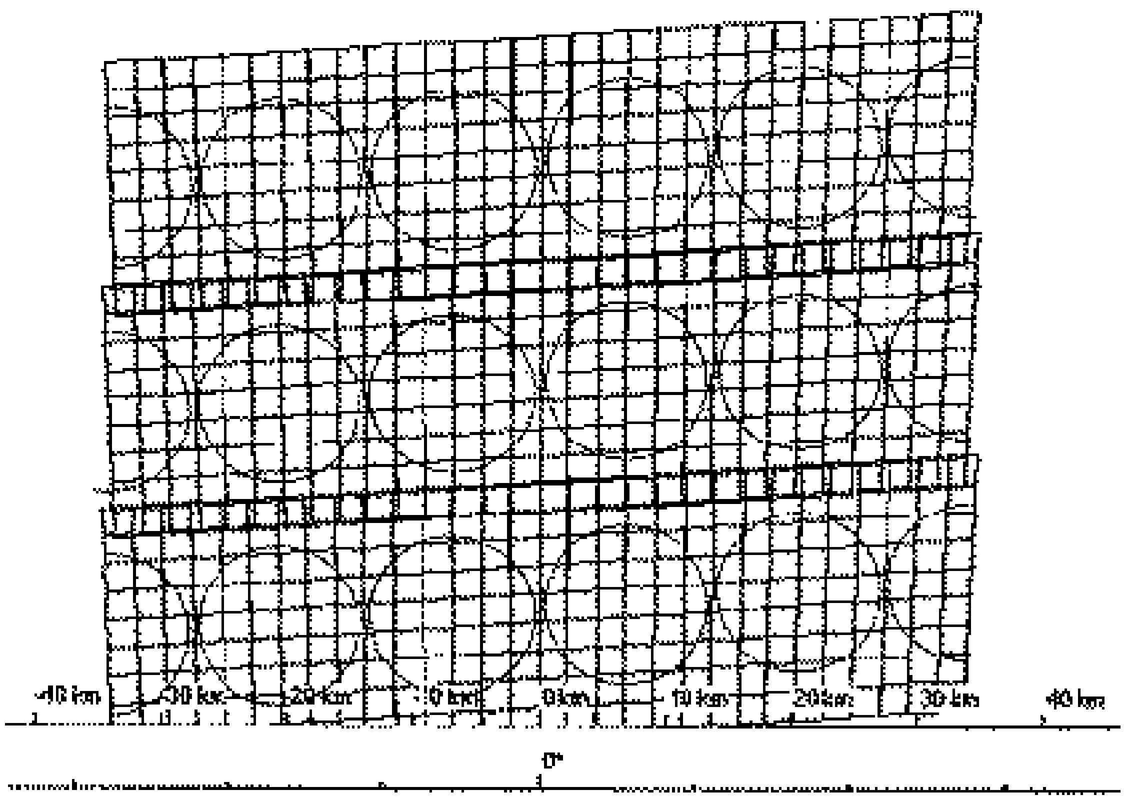


FIGURE 2.3. PROJECTION OF INFRARED (CIRCULAR) AND VIS (SQUARE) PIXELS AT NADIR

Each VIS pixel corresponds to a square region on the detector 250 µm on a side. As shown in Fig. 2.4, however, this region is actually subdivided into 10 smaller elements, each 25 µm along-track, and 250 µm across-track. Each sub-element therefore images a region 0.0185 by 0.185. A single pixel is formed by averaging the output of 10 sub-elements. To allow for fine along-track alignment of the channels, each linear array actually contains 128 sub-elements, with software control of the starting point for which 90 sub-elements are used. A final detail to be aware of is that the 90 sub-elements of each channel are read sequentially, with 6 µs between samples. Due to scan mirror motion, this offsets each sub-element 0.157% of a pixel in the across-track direction from the previous sub-element. The offset between the first and last sub-element of a 9 pixel sample is 13.95% of a pixel.

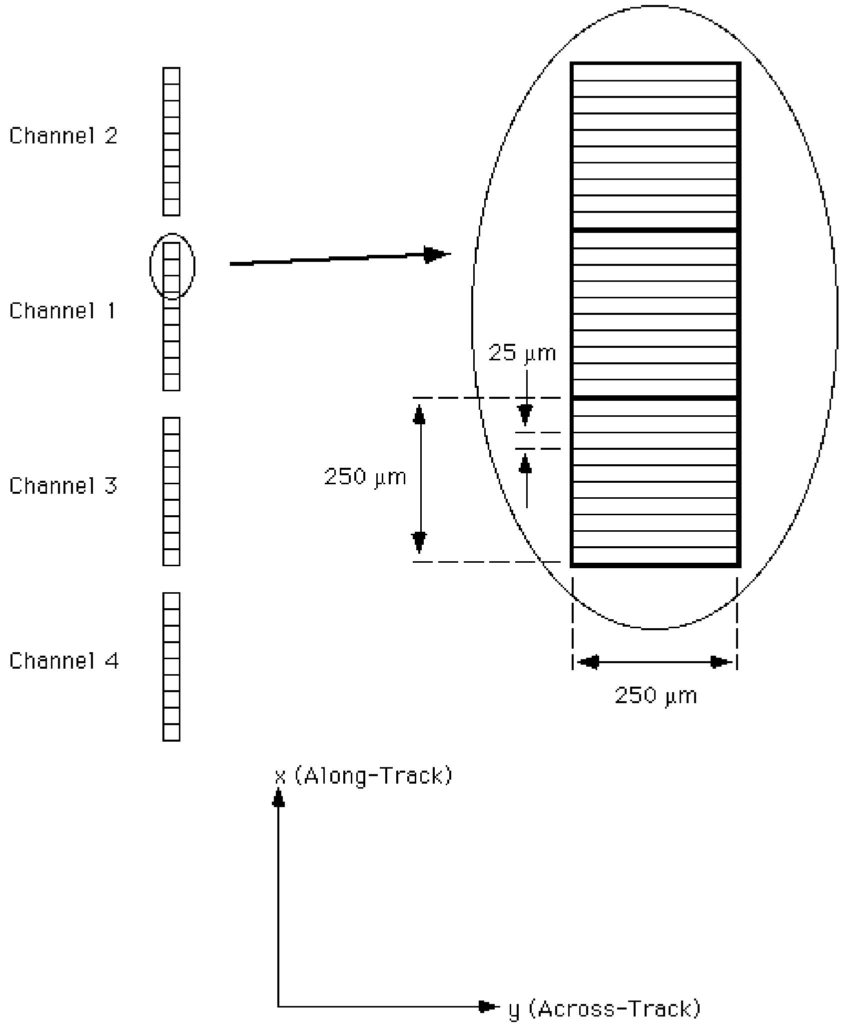


FIGURE 2.4. SCHEMATIC LAYOUT OF VIS DETECTORS

VIS GEOMETRIC MODEL

For proper characterization and validation of the VIS channels, it is necessary to have specific mathematical models of both their geometric and spectral properties. This section summarizes the geometric instrument model. A more complete discussion is provided in the AIRS VIS/NIR Geolocation Algorithm Document (Jovanovic′ and Hofstadter 1997).

The VIS geometric instrument model is a collection of parameters, shown in the table below. Knowledge of these parameters allows the line-of-sight vector associated with any pixel to be determined in the instrument coordinate system. The instrument coordinate system, or ICS, is a Cartesian coordinate system with origin at the perspective center of the optical system, the z-axis bisects the scanning angle and is positive towards nadir, the x-axis is anti-parallel to the rotation axis of the scan mirror, and the y-axis makes the system right handed. Each of these parameters will be measured on the ground, and a subset of them will be verified/refined using in-flight calibration as described in Jovanovic′ and Hofstadter 1997.

Table 2.1: Visible Instrument Geometric Model

Geometric Parameters	Nominal Value
Effective Focal Length	77.427 mm
Nominal number of pixels across-track in one scan	540
Nominal number of pixels along-track in one scan	9
Coefficients to account for non-linearity of scan rate	[0, 1, 0, 0]
Scan mirror tilt	45°
Total across-track angular coverage	99.0°
Total along-track angular coverage	1.665°

Most of the parameters in Table 2.1 are self-explanatory. To allow for non-linearities in the instrument scan rate across-track, a polynomial can be determined relating across track column number to the column number that would result from a perfectly uniform scan. (Non-linearities can arise in either the scan mirror motion or the detector readout process.) The array indicated holds coefficients for a third order polynomial: shown is the nominal case of uniform sampling.

To relate VIS pixels to ground coordinates or the coordinate systems of other instruments, additional parameters must be known. One possible set of such variables is:

- Time stamp for a reference point within a scan.
- Pixel row and column number of the reference point.
- Spacecraft orbital parameters.
- Relative alignment of the ICS with the spacecraft coordinate system.
- Scan mirror rotation period.
- Time interval between reading consecutive pixels in an array.
- Time interval between consecutive readouts of the same pixel.
- Time offsets between the four channels.

INSTRUMENT SPECTRAL AND PHOTOMETRIC MODEL

To characterize and validate the instrument, we not only need to have a model for where the instrument is pointing, but also how it responds to radiation in that direction. The spectral model consists of effective filter functions for each channel, as shown in Fig. 2.5. The photometric model is the standard calibration relation that converts instrument data numbers to absolute radiance:

$$R = \alpha \times (DN) + \beta , \tag{2.4}$$

where R is the radiance, DN is the instrument measured data number, and α and β are the gain and offset, respectively, which are different for each VIS channel (this equation is similar in form to the IR calibration equation). Filter functions, gains, and offsets will be measured pre-launch, with updates provided by on-orbit calibration routines. (See Aumann *et al.* 1996 and Section 4.3.3 of this document.)

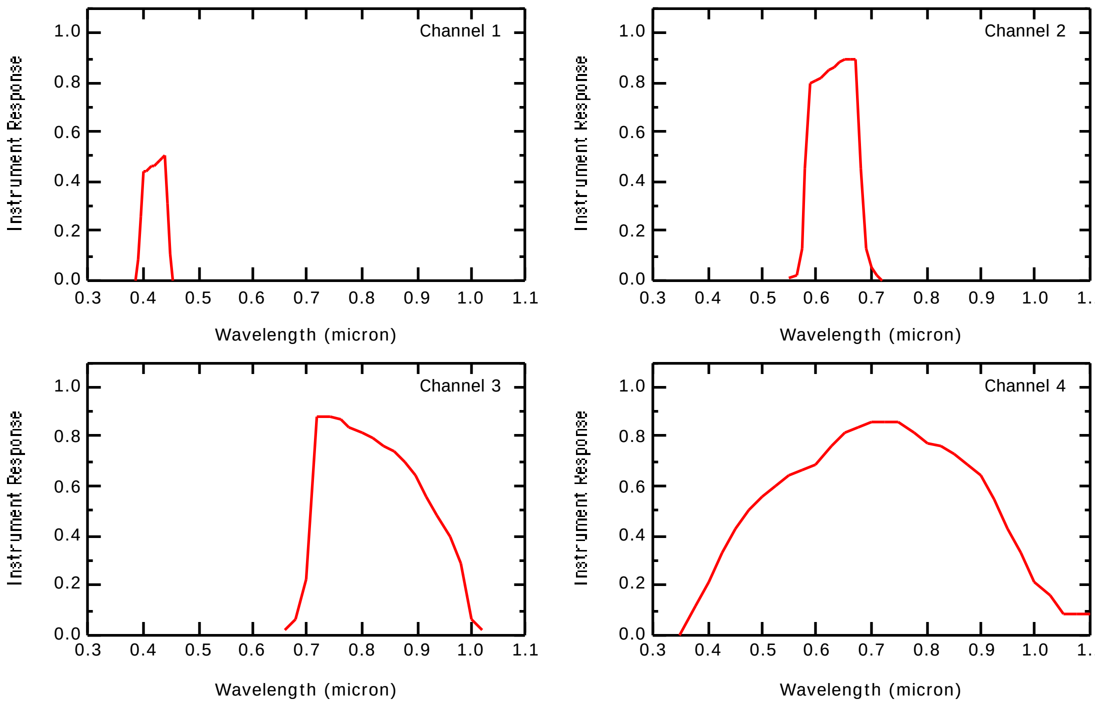


FIGURE 2.5. ESTIMATED BEGINNING OF LIFE CHANNEL RESPONSE FUNCTIONS

2.1.1c AMSU-A

AMSU-A is a cross-track scanning multispectral microwave radiometer, with a 3.3° IFOV. It is implemented as two independent instrument modules. AMSU-A1 has 13 spectral channels (50 GHz - 90 GHz) and AMSU-A2 has 2 spectral channels (23 GHz - 31 GHz). Each cross-track scan produces 34 sets of measurements (30 Earth looks, 2 dark space calibration, and 2 internal blackbody radiometric calibration). The scan repeats every 8 seconds, being synchronized with every 3 AIRS scans (via the spacecraft master clock).

2.1.1d HSB

HSB is a cross-track scanning multispectral microwave radiometer, with a 1.1° IFOV and 4 spectral channels (150 GHz - 183 GHz). HSB is identical to the AMSU-B instrument, with the exception of having one less channel (removed as a cost saving measure). Each cross-track scan produces 98 sets of measurements (90 Earth looks, 4 dark space calibration, and 4 blackbody calibration). The scan repeats every 8/3 seconds, being synchronized every third scan line.

Microwave Calibration

As described in Section 2 (Instrument description) of the Microwave L1B ATBD, each microwave antenna/receiver system — of which there are four (AMSU-A1-1, AMSU-A1-2, AMSU-A2 and HSB) — measures the radiation from two calibration sources during every scan cycle. The first source is the cosmic background radiation emanating from space. This source is viewed immediately after the earth has been scanned. The antenna is quickly moved to point in a direction between the earth's limb and the spacecraft's horizon. There it pauses (AMSU-A) or drifts slowly (HSB) while either 2 (AMSU-A) or 4 (HSB) measurements are taken. The second source is an internal blackbody calibration target which is at the ambient internal instrument temperature (typically, 10-15°C). This source is viewed immediately after the space calibration view. The antenna is again quickly moved, to point in the zenith direction, where the blackbody target is located. Again, the antenna pauses or drifts slowly while either 2 or 4 measurements are taken. Thus, two sets of calibration measurements which bracket the earth scene measurements are obtained for every scan cycle, i.e. every 8 seconds (AMSU-A) or every 2.67 seconds (HSB). A full discussion of calibration issues will be provided by the instrument manufacturer, Aerojet on delivery.

Such a through-the-antenna calibration system allows most system losses and spectral characteristics to be calibrated, since the calibration measurements involve the same optical and electrical signal paths as earth scene measurements. (The only exception is that the internal calibration target appears in the antenna near field and can reflect leakage emission from the antenna. That effect is taken into account in the calibration processing, however.) This approach has a significant advantage over calibration systems using switched internal noise sources injected into the signal path after the antenna.

The purpose of the calibration measurements is to determine accurately the radiometer transfer function, which relates the measured digitized output (i.e. counts, C) to the associated radiance:

$$R = F(C) \tag{2.5}$$

This function depends primarily on channel frequency and instrument temperature, but it could also undergo periodic and long term changes due to gain fluctuations and drift due to aging and other effects. Note that by "radiance" we refer to both the physical quantity called radiance, which has units of mW/m^2-sr-cm^{-1}, as well as the quantity called brightness temperature, which has units of K. We will specify which quantity is referred to only when it is necessary to distinguish between the two.

If the transfer function were perfectly linear, then two calibration points would uniquely determine its form at the time of the calibration measurements, since two coefficients could then be computed:

$$F_{\text{lin}}(C) = a_0 + a_1 C \tag{2.6}$$

While it has been a design goal (and a requirement) to make the transfer function as linear as possible, in reality it is slightly nonlinear. To account for the slight nonlinearities we will add a quadratic term, which will be based on pre-launch test data and actual instrument temperatures — i.e. we will assume that the nonlinear term is purely a function of instrument temperature and that its functional form does not change from its pre-launch form. Each of the four receiver systems is treated independently in this respect — each has a measured temperature (such as the RF shelf temperature or a mixer temperature) which may be associated with the nonlinearity. Thus, we assume the following form:

$$F\,(C) = a_0 + a_1C + a_2C^2 \tag{2.7}$$

The transfer function may also be expressed in terms of two system parameters — the gain, g, and the nonlinearity term, q:

$$F\,(C_s) = R_s = R_w + (C_s - C_w)/g + q \tag{2.8}$$

where the gain is given by

$$g = (C_w - C_c)/(R_w - R_c) \tag{2.9}$$

where w refers to warm and c for cold. The nonlinear term is given by

$$q = u(C_s - C_w)(C_s - C_c)/g^2 \tag{2.10}$$

Here u is a parameter which is assumed to depend on the instrument (i.e. receiver) temperature only and has been determined from pre-launch testing data.

Table 2.2: AMSU-A1 engineering data used for calibration processing

A1-1 RF shelf temperature [backup: A1-1 RF MUX temperature]
A1-2 RF shelf temperature [backup: A1-2 RF MUX temperature]
A1-1 Warm load temperatures (5)
A1-2 Warm load temperatures (5)
A1-1 PLLO selector (primary/redundant)
Cold cal. position selector (0, 1, 2, or 3)
Mode (full-scan, nadir-stare, warmcal-stare, coldcal-stare, off)

Table2.3: AMSU-A2 engineering data used for calibration processing

RF shelf temperature	[backup: A2 RF MUX temperature]
Warm load temperatures (7)	
Cold cal. position selector (0, 1, 2, or 3)	
Mode (full-scan, nadir-stare, warmcal-stare, coldcal-stare, off)	

Table 2.4: AMSU-B engineering data used for calibration processing

183-GHz Mixer temperature [backup: 89- or 150-GHz Mixer temperature]
Warm load temperatures (7)
Cold cal. position selector (0, 1, 2, or 3)
Mode (full-scan, nadir-stare, warmcal-stare, coldcal-stare, off)

More details can be found in the AIRS L1B ATBD, Part 2 and in Aerojet report 10371.

2.1.2 Atmosphere Model

The atmospheric pressure layering grid for the atmospheric model was selected to keep radiative transfer errors well below the instrument noise. Grid characteristics are a function of the spectral region(s) of observation, the instrument resolution, and instrument noise. The speed of the final fast transmittance model will depend on the number of layers, so excessive layering should be avoided.

Radiative transfer simulations indicate some channels need a top layer with pressures as small as 0.01 mb, an altitude of ~ 80 km. The region of primary importance to AIRS/AMSU-A/HSB is the troposphere and lower stratosphere, where layers on the order of 1/3 the nominal 1 km vertical resolution of AIRS retrievals are desired. Smoothly varying layers facilitate interpolation and avoid large changes in layer effective transmittances. The following relation defines the pressure layer boundaries selected for AIRS:

$$P_i = (ai^2 + bi + c)^{7/2} \tag{2.11}$$

where P is the pressure in mb; i is the layer boundary index and ranges from 1 to 101; and the parameters a, b, and c were determined by solving this equation with the following fixed values: P_1 = 1100 mb, P_{38} = 300 mb, and P_{101} = 5x10^{-3} mb. The 101 pressure layer boundaries in turn define the 100 layers. These layers vary smoothly in thickness from several tenths of a kilometer near the surface to several kilometers at the highest altitudes. Figure 2.6 displays a plot of this atmospheric layer structure.

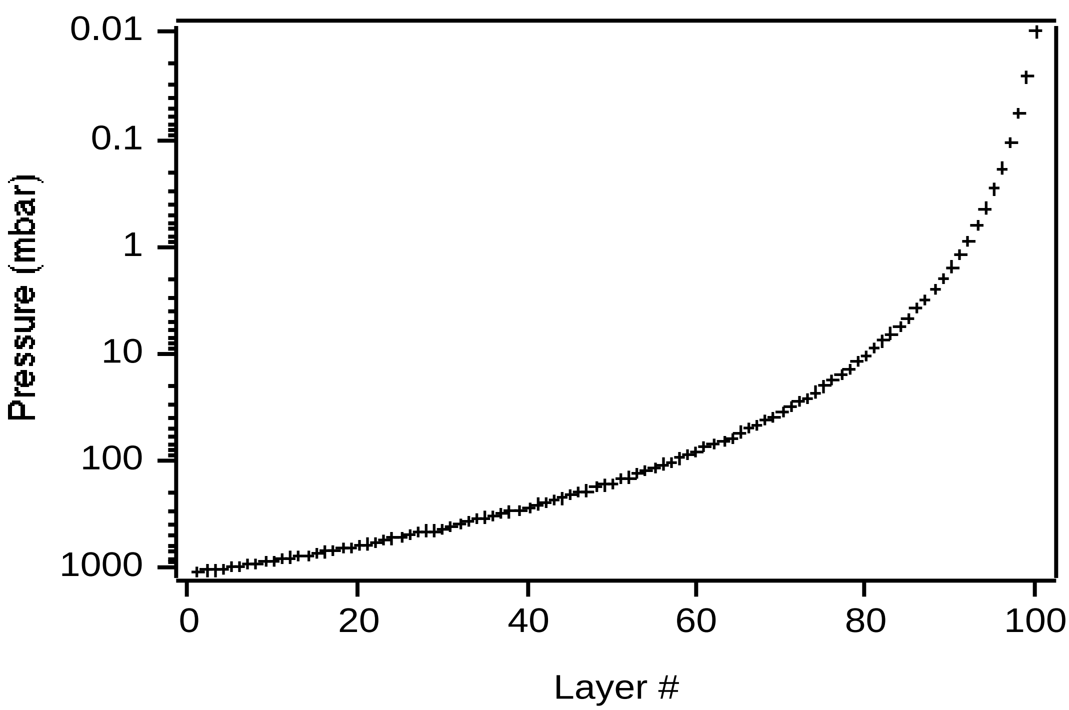


FIGURE 2.6: ATMOSPHERIC MODEL PRESSURE LAYER STRUCTURE.

A single state (atmospheric and surface properties) is retrieved from an ensemble of 9 AIRS, 9 HSB scenes, and 1 AMSU-A scene. The union of AIRS, HSB and AMSU scenes and the enclosed unobserved regions are the horizontal extend of the retrieved state and is referred to as the "retrieval footprint". The atmosphere and surface properties are assumed to be horizontally homogeneous within the footprint, except for cloudiness. Cloudiness may be composed of two opaque (in the infrared) layers each of uniform cloud top height; the layers may be disjoint. The retrieved state at a given height is representative of those regions of the footprint not obscured by clouds. Information about the state of levels completely obscured by clouds is obtained solely from microwave channels, in which case those levels are assumed to be homogenous. In summary the retrieved state describes a height-dependent horizontal region where the extend of the horizontal region depends on the height and position of clouds.

2.1.3 Radiance Model

In the following, atmospheric radiative transfer or the 'forward problem' will be discussed. Because the retrieval methodology utilized by the AIRS team depends on the ability to accurately determine the outgoing radiance, particular attention will be paid to errors in the spectroscopy and errors in modeling the outgoing radiation -- the rapid forward model. The transmittance of multiple layers is calculated by taking the product of the transmittances for each layer. This transmittance is then used in the radiative transfer equation to compute brightness temperature. For microwave channels,

$$\begin{aligned}\Theta = & \int_0^{P_S} T(P) < d\tau(0,P) > + \varepsilon T_S < \tau(0,P_S) > \\ & + (1-\varepsilon) < \tau(0,P_S) > \int_0^{P_S} T(P) < d\tau(P_S,P) > + (1-\varepsilon)\Theta_C < \tau(0,P_S) >^2\end{aligned} \qquad (2.12)$$

where T(P) is atmospheric temperature at level P, T_s and P_s are the surface temperature and pressure, Θ_c is the cosmic background brightness temperature (see eq. 4.1.2, AIRS L2 ATBD), and ε is the emissivity of the surface, assumed to be smooth here.

For infrared radiances, the monochromatic radiance leaving the top of the atmosphere, excluding scattering and clouds and assuming a Lambertian surface is approximated by

$$\begin{aligned}R(\nu,\theta) = & \varepsilon_s B[\nu,T_s]\tau(\nu,p_s,\theta) + \int_{\ln p_s}^{\ln p_\infty} B[\nu,T(p)]\frac{\partial\tau(\nu,p,\theta)}{\partial \ln p}\, d\ln p + \\ & (1-\varepsilon_s)\tau(\nu,p_s,\theta)\int_{\ln p_s}^{\ln p_\infty} B[\nu,T(p)]\frac{\partial\tau(\nu,p,\theta)}{\partial \ln p}\, d\ln p + \rho_s H(T_{sun})\tau(\nu,p_s,\theta)\tau(\nu,p_s,\theta_{sun})\cos(\vartheta_{sun})\end{aligned}$$

(2.13)

where $B[\nu,T(p)]$ is the Planck function emission for layer p at temperature T(p), $\tau(\nu,\theta)$ is the layer-to-space transmittance at viewing angle θ, $\tau_s(\nu,\theta)$ is the surface-to-space transmittance, and T_s, ε_s, and ρ_s refer to the Earth's surface temperature, emissivity, and reflectivity respectively. Also, $H(\nu)=2.16\text{x}10^{-5}\ \pi\ B(\nu,T_{sun})$.

For forward modeling of visible/near-IR radiances, the radiative transfer equation is numerically integrated using a discrete ordinate algorithm described in Stamnes *et al.* (1988). This algorithm allows for multiple scattering, and assumes a plane-parallel atmosphere. Both thermal radiation and reflected solar energy are accounted for. Atmosphere, aerosol, cloud, and surface properties are controlled primarily by input files, though use is also made of default values internal to the software. Thus, the user has the option of using the 100 layer model described in Section 2.1.2 to define atmospheric temperature, pressure, water vapor, and ozone profiles, or one of six reference atmospheres hardwired within the code. (The reference atmospheres are tropical, mid-latitude summer, mid-latitude winter, sub-arctic summer, sub-arctic winter, and the US 1962 Standard Atmosphere, all from McClatchey *et al.* 1972.) Atmospheric transmission is then determined using the low resolution band models developed for LOWTRAN 7 (Pierluissi and Marogoudakis, 1986), as modified by Wiscombe and Evans (1977) to account for non-Beers Law behavior due to the coarse spectral resolution. (The non-Beers Law effects arise because of the atmospheric transmission varying across a band, resulting in the effective transmission of one layer depending on the previous layers penetrated.)

Boundary layer and stratospheric aerosols are modeled based on LOWTRAN 7. For boundary layer aerosols, the input files specify visibility, optical depth, and aerosol type, which the software then uses to create vertical aerosol abundance profiles. Scattering properties (which are a function of relative humidity) are matched to one of five types: none, rural, urban, oceanic and tropospheric. Stratospheric aerosols also have five types (none, background, aged volcanic, fresh volcanic, and meteor dust), with the user controlling the altitude, optical depth, and aerosol type for up to 5 layers.

Cloud optical properties are modeled with a look-up table, the table having been prepared using Mie theory for spherical particles. Up to five cloud layers can be specified. For liquid clouds, the particle effective radius is provided by the user, and a gamma distribution is assumed. Ice clouds are assumed to have an empirical size distribution with an effective radius of 106 microns. Total water content or optical depth is set by the user for each cloud layer.

The VIS simulation software contains default surface scattering properties for four surface types: snow, ocean, sand, and vegetation. All are assumed to be Lambertian. Any linear combination of these four types can be used in the forward model. In addition to the factors already discussed (atmosphere, aerosol, cloud, and surface properties), the forward model accounts for solar position, viewing zenith and azimuth angles, and instrument spectral response.

2.1.4 Radiance Validation

Validation of AIRS radiances with HIS

The radiance validation of the AIRS instrument is an essential element for any of the AIRS science data products. There are both pre-launch and post-launch radiance validation tasks.

Most of the pre-launch activities involving the AIRS instrument are best identified as instrument performance *characterization* rather than *validation*. However, a pre-launch AIRS IR radiation validation could be performed by using the AIRS instrument to acquire downwelling atmospheric radiance observations coincident with the University of Wisconsin AERI ground-based interferometer. The AERI instrument was designed as a spectral radiance standard for the DOE ARM program and can provide an excellent reference for the comparison of AIRS observations to radiative transfer calculations of the downwelling infrared emission spectrum. This ground-based radiance validation should provide an early warning of any potential problems well in advance of the expected launch of the EOS PM-1 platform in the year 2000.

Validation of AIRS IR radiances falls into two categories: spectral and radiometric. The former deals with identification of inconsistencies due to AIRS channel central frequencies and spectral response function full-width uncertainties, and the latter with intensity of radiances. The post-launch validation of AIRS radiances will include a validation of the spectral and radiometric calibration algorithms used to convert the raw signal counts of each channel to scientific units at known wavenumber positions. In the early post-launch phase, the spectral position calibration of the AIRS radiances can be validated by comparison with calculations from radiative transfer models of known accuracy. This early spectral position validation will make use of data from DOE ARM program sites to characterize the atmospheric state. Following the preliminary assessment of the AIRS instrument, a dedicated flight campaign using accurately calibrated aircraft instruments will be performed. These aircraft data will be analyzed for the purpose of both spectral and radiometric radiance validation. The validation techniques will make use of AIRS Science Team members' experience with similar instrument intercomparisons in the past, adapted to the specific requirements of the AIRS validation.

Radiance validation would be performed by comparing the observed minus calculated residuals between the AIRS and HIS/NAST/Scanning HIS/AES. Matching observed and calculated radiances requires good characterization of the atmospheric state (e.g. temperature and water vapor profiles) and surface properties (surface temperature and emissivity). Ground-based in situ data, such as that acquired during the ARM Water Vapor IOP in (September 1996 and 1997), can be used to characterize the uncertainties in the tropospheric water vapor and temperature profiles to within 5% RH and 0.5 K respectively. This characterization of the atmospheric state parameter uncertainties, particularly water vapor, is crucial for validation of AIRS radiances.

Direct comparison of AIRS and HIS/NAST/Scanning HIS/AES radiances is possible by differencing residuals between measurements and accurate forward calculations and exploiting the correlation between forward model calculations errors to reduce the error of the difference. Further improvements in the comparison are expected by applying each instrument's Spectral Response Function (SRF) to the other. The errors in the uncorrected residuals are expected to be dominated by calibration errors, lack of knowledge of the atmospheric state above the aircraft, and spatial heterogeneity and collocation. This approach can be understood using an example, based on simulating the operational environment of CAMEX I.

The residual differences are defined as,

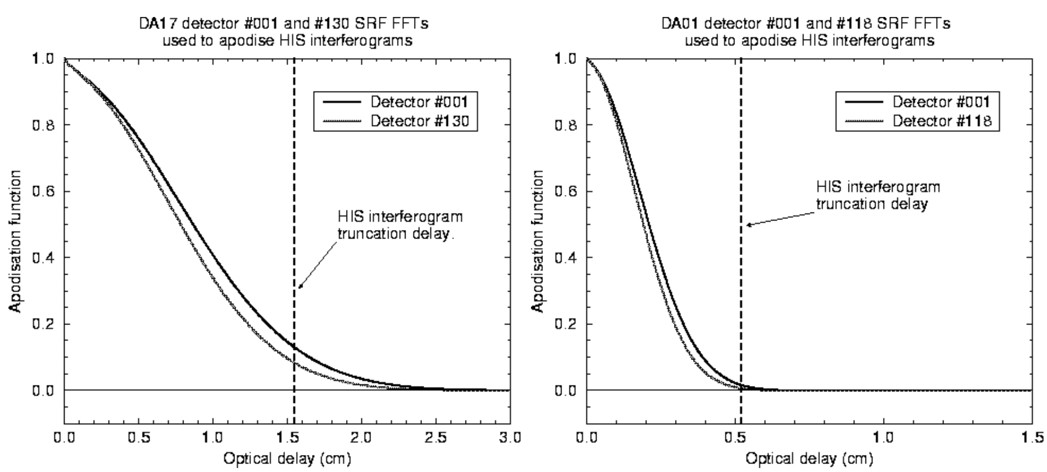
$$(AIRS_{meas} - AIRS_{calc}) - (HIS_{meas} - HIS_{calc}) \tag{2.14}$$

In this simulation study *measurement* refers to calculations using the CAMEX I sonde data from September 29, 1993 and *calculation* refers to calculations with a temperature or water vapor perturbation applied to the sonde data. The perturbations applied were a 0.5K offset to the entire temperature profile and a 5% increase in the water vapor amount also applied throughout the atmospheric column. These values are indicative of the accuracy of sonde measurements that can be achieved.

To minimize the residual due to instrument differences, the SRFs of each instrument were applied to the other. To approximate AIRS radiances using HIS resolution data, the HIS interferograms were apodized with the Fourier transform of each individual AIRS detector SRF. The AIRS SRFs used were derived from the Lockheed-Martin definition derived from the AIRS spectrometer optical model,

$$SRF_{AIRS}(n-n_o) = \exp\left[-a(n-n_o)^2\right] + b\left(1-\exp\left[-a(n-n_o)^2\right]\right)\left(|n-n_o|+d\right)^c \qquad (2.15)$$

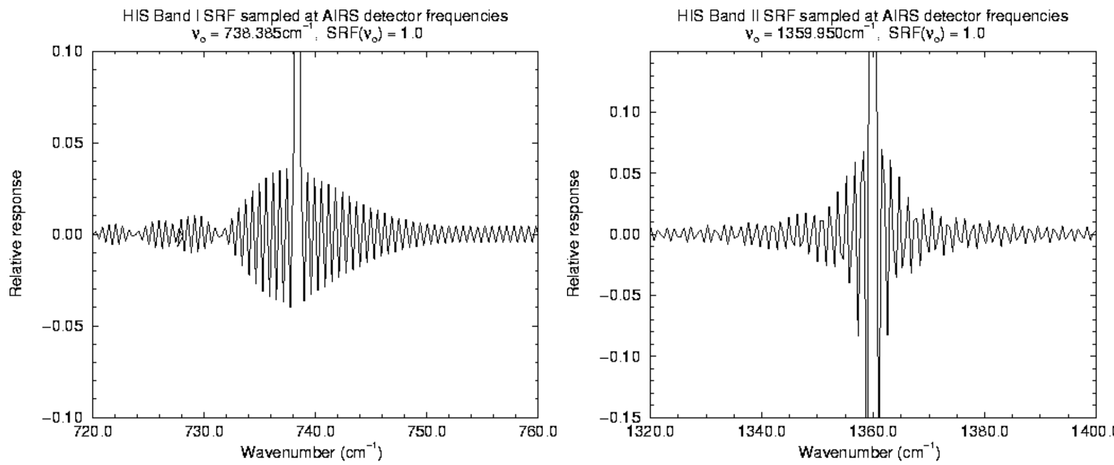
where ν_o is the central frequency and *a*, *b*, *c*, and *d* are predetermined coefficients. Figure 1 shows the apodization functions used for the first and last detectors in AIRS detector arrays 17 (longwave, falls within HIS Band 1) and 01 (shortwave, falls within HIS Band 3). As shown, for some detector arrays the AIRS SRF in the interferometric domain extends past the maximum optical delay (figure 1a); and for others the AIRS apodizations function fall nearly to zero at the maximum HIS optical delay (figure 2.7). The approximation of AIRS $\rightarrow$ HIS radiances is more accurate for those cases where the apodization function is more fully included within the HIS optical delay range. The resultant apodized interferograms are padded out with zeros before Fourier transformation to the spectral domain to allow interpolation of the radiances to the AIRS channel frequencies.



(a) (b)

FIGURE 2.7 FOURIER TRANSFORMS OF AIRS SRFS USED TO APODIZE HIS INTERFEROGRAMS.
(A) AIRS DETECTOR ARRAY 17. (B) AIRS DETECTOR ARRAY 01.

To approximate HIS radiances using AIRS resolution data, the AIRS radiances were convolved with the Fourier transform of the HIS interferogram truncation boxcar. The sinc function resulting from the transform of the boxcar was sampled at the AIRS frequencies. The sampling frequency produced beating effects with the sinc function itself. Figure 2.8 shows the HIS SRFs used for two AIRS channels.

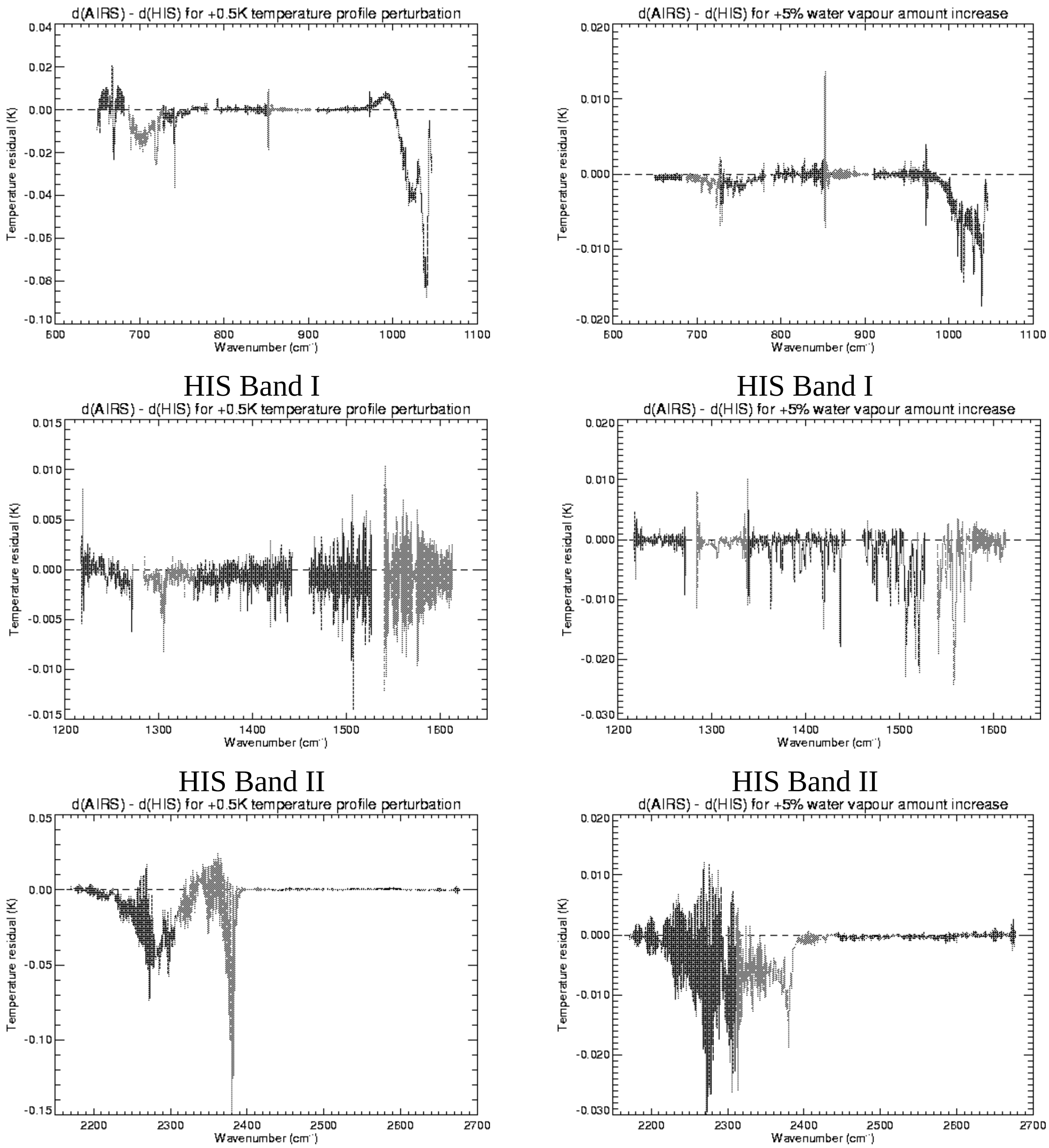


(a) (b)

FIGURE 2.8 FOURIER TRANSFORMS OF HIS BOXCAR FUNCTION SAMPLED AT THE AIRS DETECTOR ARRAY CENTRAL FREQUENCIES. (A) AIRS CENTRAL FREQUENCY 738.385 CM^{-1}. (B) AIRS CENTRAL FREQUENCY 1359.950 CM^{-1}.

Residuals were calculated for three conditions to examine instrument, altitude and zenith angle effects: 1) the AIRS and HIS at the same altitude; 2) the HIS at nominal flight altitude (55 mb); and 3) AIRS zenith angle of 30°, HIS at nominal flight altitude. The residuals for each case are shown in figures 2.9 - 2.11 respectively. The residuals due to instrument differences alone are of the order of a few hundredths of a degree except for the 4.3 μm region. This is due mainly to the resolution differences between the AIRS and HIS in the shortwave. The spacing of the AIRS channels in this region does not allow the HIS SRF to be sampled well which is emphasized in the convolved radiances due to the large change in radiance across the CO_2 absorption band. The effect also occurs at shorter wavelengths but is not as noticeable due to the lack of significant spectral features from ~3.7-4.1μm. The effect of altitude differences, figure 2.9, is most noticeable in the 15μm CO_2 and 9.6μm O_3 absorption regions. Here the difference in absorption is due to the atmosphere between the instruments. For the water vapor region, larger residuals are not found as most of the absorption still occurs below the altitude of the HIS. The effect of different view angles is also apparent in figure 2.10 even though the magnitudes are still small. Most affected are the less opaque and window regions.

Temperature perturbation **Water vapor amount perturbation**



HIS Band III HIS Band III

FIGURE 2.9. AIRS/HIS RESIDUALS DUE TO INSTRUMENT AND ALTITUDE DIFFERENCES. HIS INSTRUMENT AT NOMINAL FLIGHT ALTITUDE OF 55 MB.

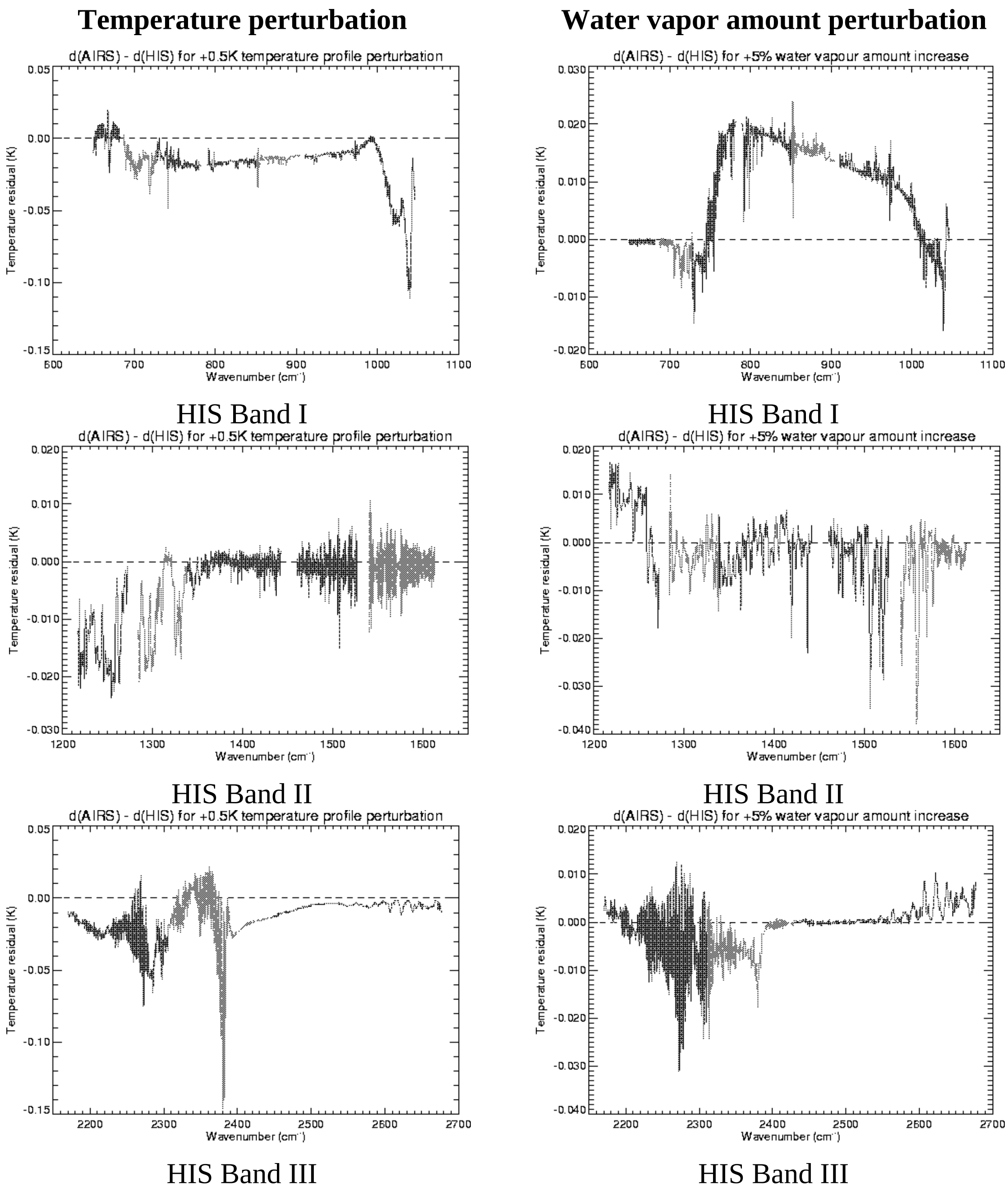


FIGURE 2.10 AIRS/HIS RESIDUALS DUE TO INSTRUMENT, ALTITUDE, AND ZENITH ANGLE DIFFERENCES. HIS INSTRUMENT AT NOMINAL FLIGHT ALTITUDE OF 55 MB.

Validation of Microwave Radiances

The same approach of analyzing residual differences will be used in validating the microwave radiances, but will include aircraft and satellite based instruments. One potential instrument is the Millimeter-wave Imaging Radiometer (MIR), which is often flown during field campaigns and has a spectral coverage nearly identical to that of HSB. Satellite based instruments (e.g., AMSU-B on NOAA satellites and SSM/T-2 on DMSP satellites)) may also be used, but only to the extent that collocation and simultaneity requirements are met.

Available intercomparison data for AMSU-A are somewhat more limited. The planned NASTM aircraft instrument will make it possible to validate some of the AMSU-A temperature sounding channels, and AMSU-A on NOAA satellites can be used, again subject to collocation and simultaneity requirements.

Satellite-based instruments are potentially poorer controlled than aircraft-based instruments and may not be as well calibrated at the time of measurement. Therefore comparisons with satellite-base radiances will be used vicariously and only when better data are not available.

Radiance Validation by Forward Model Radiance Intercomparisons

For special atmospheric conditions, radiative transfer calculations for some channels can have unusually high accuracies because of a combinations of weak sensitivity to surface and atmospheric structure, small spectroscopic parameter inaccuracy, and spectroscopic calibration errors. For these conditions, computed radiances from correlative data can have accuracies better than the absolute radiometric calibration and can be used for validation purposes.

One set of potential opportunities involve surface channels (e.g. the 920 cm^{-1} , 1175 cm^{-1}, 2613 cm^{-1} and 2686 cm^{-1} channels have near unity atmospheric transmissivity) viewing the ocean surface under cloud-free conditions. One site might be the Gulf of Mexico during the summer when sea surface temperature are small and “bucket” sea surface temperatures should be accurate to about 1 K. Calculated radiances derived from correlative measurement of atmospheric water vapor burden, atmospheric temperature profile and sea surface temperature should have an accuracy of around 1-2% allowing for conservative spectroscopic and correlative measurement errors.

Another potential site is the high latitude winter polar regions of the lower polar stratosphere. In these regions, diabatic decent tends to bring the atmospheric lapse rate close to zero over a vertical region extending 15 to 30 km. For these conditions errors in spectroscopic parameters that affect the saturation level for lower stratospheric channels produce minimal change to the calculated radiance. Using stratospheric temperature profiles derived from radiosondes, and selecting those radiosondes having the smallest lapse rates, it should be possible to validate absolute radiometric calibration to 2-4 K in brightness temperature (1-2%). Small signal to noise at the low temperatures of the winter stratosphere poses one problem which will need to be addressed but should be manageable by averaging of radiances over the large horizontal scales of stratospheric disturbances.

Radiance Validation using Empirical Orthogonal EOFs

The correlated spectral nature of the infrared radiances will be exploited on a temporal and spatial basis by calculating the empirical orthogonal functions of the correlation matrix as described in Haskins et al. (1997). The usefulness of this approach stems from the fact that statistical properties of the Level 1B radiances are used and not the derived Level 2 geophysical parameters. EOFs provide an ordered set of functions representing the covariance in a domain, and the EOFs explaining a significant proportion of the variance have physical significance. This approach can also be applied in the spectral (frequency) domain. Since different frequencies correspond to different emission levels and to different constituents (gaseous, cloud, aerosol, surface), maps of covariance are strong indicators of important features of atmospheric behavior.

For completeness, the EOFs are defined from the data:

$$\dot{\mathbf{D}}'(\mathbf{x},t,\nu) = \mathbf{D}(\mathbf{x},t,\nu) - \overline{\mathbf{D}}_{\mathbf{x},t}(\nu) \qquad (2.16)$$

a function of space, time, and frequency and where $\overline{\mathbf{D}}_{\mathbf{x},\mathbf{t}}$ is the space-time average. The data at this particular place and time, and time average, may be regarded as a vector whose components are 720 discrete frequencies which make up the spectrum. For the standardized data we define

$$\mathbf{D}'(\mathbf{x},t,\nu) = \frac{\left(\mathbf{D}(\mathbf{x},t,\nu) - \overline{\mathbf{D}}_{\mathbf{x},t}(\nu)\right)}{\sigma(\nu)}. \qquad (2.17)$$

The EOFs, $\varphi^{(i)}(\nu)$, are also vectors, i.e. spectra, and from the covariance matrix, $\mathbf{E}(\nu)$, as expressed in equations (3) and (4)

$$\mathbf{E}(\nu) = Cov_{\mathbf{x},t}\langle \mathbf{D}'(\mathbf{x},t,\nu)\rangle \qquad (2.18)$$

$$\mathbf{E}(\nu)\varphi^{(i)}(\nu) = \lambda^{(i)}\varphi^{(i)}(\nu). \qquad (2.19)$$

Projecting the data against the EOFs allows the calculation of the space-time amplitudes which are presented in figure 14 averaged over space and in Plate I averaged over time. Using the orthonormality of the EOFs it can be shown,

$$\mathbf{A}^{(i)}(\mathbf{x},t) = \mathbf{D}'(\mathbf{x},t,\nu)\varphi^{(i)}(\nu) \qquad (2.20)$$

where $\mathbf{A}^{(i)}(\mathbf{x},t)$ is the i^{th} component of the amplitude.

2.1.5 Level 2 Error Analysis

Error analysis is the mathematical prediction of retrieved parameter error based on estimates of instrument measurement error, atmospheric and instrumental model error, and mathematical instability associated with the inverse operator. The analyses follow the formalism of Rodgers (1990) and will

- estimate precision, accuracy and stability of retrieved parameters
- optimize vertical resolution of profile quantities based on trade-off studies between resolution and precision
- study the interpretation of smoothed parameters in the presence of horizontal spatial heterogeneity
- study the sensitivity of retrieved parameters to cloud property parameterization
- estimate the tuning period (the time between tuning parameter adjustments to maintain accuracy within specified limits)

The AIRS Unified Retrieval is a 5 step process comprised

1. of an initial microwave retrieval which includes a climatological a priori
2. a cloud clearing of the AIRS radiances by affine transformation using the step 1 retrieval
3. a statistical retrieval from the HSB, AMSU-A and AIRS cloud cleared radiances based on linear regression around a mean correlative state (training set)
4. a physical retrieval using the statistical retrieval result as virtual measurements, temperature, water vapor and surface properties are individually retrieved
5. a two stage iteration involving

    A. a second cloud clearing similar to step 2, based on the step 4 retrieval products or step 5 products of the previous iteration

    B. a physical retrieval of the cloud cleared radiances using the step a cloud cleared radiances and a stabilizing operator (no virtual measurements)

for the purposes of these analyses, the estimated state vector $\mathbf{X}$ is treated as the product of a nonlinear contribution function $\mathbf{D}(\mathbf{X},\mathbf{B},\mathbf{I}_V,\mathbf{I},\mathbf{S}_B,\mathbf{S}_V,\mathbf{E})\mathbf{I}$ acting on the measured radiances $\mathbf{I}$. The contribution function depends on the solution, a vector of auxiliary parameters $\mathbf{B}$, a vector of virtual measurements $\mathbf{I_V}$, the measurements $\mathbf{I}$ (including uncleared radiances, instrument position and orientation and real time calibration data), and the covariance matrices $\mathbf{S_B}$, $\mathbf{S_V}$, $\mathbf{E}$ for the auxiliary parameters, virtual measurements and actual measurements.

The auxiliary parameters includes all data entering the retrieval not explicitly included in the algorithms. This includes spectroscopic and instrument data, numerical and statistical approximations in the radiance forward model, fixed parameters, approximations in the calibration algorithms and spatial representation, approximations Auxiliary parameters also includes and tuning and smoothing parameters of steps 2 and

5.. Virtual measurements include the a priori geophysical data used to stabilize the retrieval such as the climatological temperature and water vapor data of step 1 and the training data sets of step 3.

The total error budget, given by the solution covariance matrix **S** is

$$\mathbf{S} = \mathbf{D}\left\{\mathbf{E} + \mathbf{K}_B^T \mathbf{S}_B \mathbf{K}_B + \mathbf{K}_V{}^T \mathbf{S}_V \mathbf{K}_V\right\}\mathbf{D}^T \tag{2.1.21}$$

where the weighting functions $\mathbf{K}$, $\mathbf{K_S}$, $\mathbf{K_V}$

$$\mathbf{K} = \frac{\partial\,\mathbf{I}}{\partial\,\mathbf{X}} \qquad \mathbf{K}_B = \frac{\partial\,\mathbf{I}}{\partial\,\mathbf{B}} \qquad \mathbf{K}_V = \frac{\partial\,\mathbf{I}}{\partial\,\mathbf{I}_V} \tag{2.1.22}$$

refer to changes in uncleared radiances due to changes in the state vector **X**, auxiliary parameters **B** and virtual measurements $\mathbf{I_V}$. Using definitions for error as described in appendix A, the analysis will predict the following errors.

<u>Bias</u>

The mean difference between the true state and the estimate is referred to as the bias and is given by

$$\mathbf{S} = \mathbf{D}\left\{\mathbf{K}_B \delta B + \mathbf{K}_V \delta I_V\right\} \tag{2.1.23}$$

where δB and δI_V are the biases in auxiliary parameters and virtual measurements. For those retrieved parameters that have accurate correlative data sets, tuning is expected to reduce $\mathbf{K}_B \delta B + \mathbf{K}_V \delta I_V$ to near zero.

<u>Precision</u>

Error sources contributing to precision are random on the shortest time scales. Instrumental sources include detector and electronic noise, and photon counting statistics. Errors associated with radiance cloud clearing algorithms also contribute to the precision budget because unresolved small scale structure in the cloud field behaves randomly on the length and times scales resolved by AIRS. The component of the solution covariance matrix attributed to precision is

$$\mathbf{P}^2 = \mathbf{D}(\mathbf{E} + \mathbf{E_C})\mathbf{D}^T \tag{2.1.24}$$

where $\mathbf{E}_c = \mathbf{K}_{B_c} \mathbf{S}_{B_c} \mathbf{K}_{B_c}^T$ is the component of auxiliary parameter error budget associated with cloud parameter representation.

Accuracy

Accuracy involves those errors which are correlated over the longest time scales of the life of the instrument. These include uncertainty in spectroscopic parameters, approximations in the radiance fast transmission algorithms (see Level 2 ATDB for discussion), uncertainty in instrument calibration parameters, biased virtual measurements, and biases entered through tuning.

$$\varepsilon^2 = \mathbf{D}\left\{\mathbf{K}_B^T\mathbf{S}_B\mathbf{K}_B + \mathbf{K}_V{}^T\mathbf{S}_V\mathbf{K}_V\right\}\mathbf{D}^T \qquad (2.1.20)$$

Tuning will be introduced to reduce the inaccuracy of absolute radiometric calibration, errors in spectroscopy and artifacts in radiance residuals derived from correlative data attributable to the AIRS retrieval system.

Spatial Correlation

Analyses of spatial correlations in temperature, water vapor, and cloud and surface properties provide an estimate of how well near coincident correlative data are expected to agree with AIRS retrievals in the absence of inaccuracy. As part of the pre-launch validation program, the spatial correlative of state vector parameter x_i measured a distance $d\vec{s}$ apart, $C_{ij}(d\vec{s})$, will be estimated from existing campaign data having high spatial resolution (e.g. CAMEX I and II, TOGA COARE, and FIRE). Post launch estimates of accuracy obtained through intercomparisons will be corrected using these estimates.

Horizontal Sampling and Smoothing

Retrieved atmospheric states resolve horizontal structure with the spacing of the AMSU-A footprints. The retrieved state in the absence of clouds is an area-weighted smoothing of states covered by the nine AIRS footprints included in the retrieval.

With the added complication of clouds, the retrieved state variables included states not obscured by clouds, (i.e. those at levels of the atmosphere above the clouds or those stated not containing clouds). The post-launch intercomparisons shall provide unbiased error estimate by excluding or reducing the error of those correlative data sets (e.g. radiosondes, dropspondes and LIDAR profiles) not affected by clouds or which sample cloud properties differently from AIRS. Vertical Resolution and Smoothing

As greater vertical resolution is retrieved from measurements, the estimated error increases due to the introduction in singularities into the contribution functions. The ability of the measurement system to resolve vertical structure is characterized by the averaging kernels

$$\mathbf{A} = \mathbf{DK} \tag{2.1.25}$$

which quantify how a perturbation to the geophysical state is projects onto the retrieved state. The squared difference between the averaging kernels and the identity matrix, referred to as the smoothing error.

$$\mathbf{S}_{SM} = (\mathbf{A} - \mathbf{I})\mathbf{S}(\mathbf{A} - \mathbf{I})^T \tag{2.1.26}$$

As part of the pre-launch validation studies, the AIRS simulation system will be used to generate atmospheric states having various degrees of vertical resolution. Evaluation of the smoothing error for various vertical resolutions will produce increasing smoothing error with increasing resolution and allow an optimal vertical representation.

Non-Linear Error Analyses

Infrared radiative transfer is highly nonlinear and there is some concern that the results of a linear error analysis has little relevance to the AIRS retrieval system. A generalization of the linear problem is given below provided the probability distributions for the state vectors, auxiliary parameters vectors and measurement vectors can be estimated. Generalized nonlinear weighting and contribution functions, such as

$$I = \mathbf{K}(\mathbf{X}, \mathbf{X}_B) \qquad \mathbf{X} = \mathbf{D}(\mathbf{X}, \mathbf{B}, \mathbf{I}, \mathbf{S}_B, \mathbf{S}_V, \mathbf{E}) \tag{2.1.27}$$

can be combined with probability density functions for $\mathbf{X}$, $\mathbf{B}$, $\mathbf{I}$ and $\mathbf{I_V}$, $P_{\mathbf{X}}$, $P_{\mathbf{X}}$, $P_{\mathbf{B}}$ and (provided are uncorrelated) to give a nonlinear estimated error

$$\mathbf{S} = \int \left(\mathbf{D}(\mathbf{X}, \mathbf{B}', \mathbf{I}', \mathbf{S}_B, \mathbf{S}_V, \mathbf{E}) - \mathbf{X}\right)^2 P_{\mathbf{B}'} P_{\mathbf{I}'} P_{\mathbf{I}_V} \, d\mathbf{B}' \, d\mathbf{I}' \, d\mathbf{I}'_V \tag{2.1.28}$$

Evaluations of equation 2.1.28 are most readily performed using Monte Carlo simulation, and will be used to test the validity of the linearized expressions. Nonlinear generalizations of equations 2.1.21 through 2.1.26 exist and will be studied if necessary.

2.2 Sampling requirements

There are three basic aspects of sampling which need to be dealt with: observational geometry, spatial sampling and temporal sampling.

Observational Geometry

There are three basic types of instrument scan modes that are necessary properly validate AIRS data: (1) Nadir scanning (NS) , (2) target tracking (TT), which keeps the FOV fixed and varies the scan angle, and (3) spiral (S), which keeps the scan angle fixed with respect to the target. The last two types of scan modes are to be used mainly in understanding the spectral signature at various incident sun angles and viewing geometries. For example, it has been shown (personal communication, Palluconi), that the brightness temperature in the 11 μm region can vary as much as 5° K in grassland regions depending on the viewing angle. In the microwave, where surface emissivity can be a very strong function of viewing angle, the variation may be even greater.

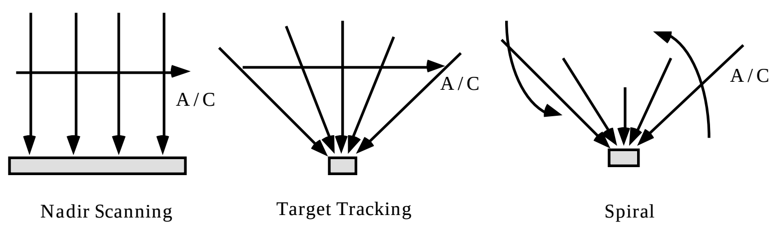


FIGURE 2.11 SCANNING GEOMETRIES

Spatial and Temporal Characteristics

According to the EOS Panel On Data Quality, the post-launch validation of AIRS/AMSU-A/HSB will need to be conducted over "......the full range of possible conditions". This implies an extensive sequence of field campaigns that address the validation performance requirements for the AIRS Standard and Research Products. Field campaigns will need to include:

(a) a tropical ocean campaign for validation of the atmospheric thermodynamic and Infrared/Microwave radiation variables, cloud properties (convective and stratus), ocean skin temperature and ocean fluxes (day and night),
(b) a polar campaign, over ice and snow cover, to assess algorithm performance for the determination of temperature and humidity profiles, cloud emissivity, skin temperature and day/night fluxes, and
(c) a sequence of mid-latitude campaigns over a well instrumented land site (possibly one of the EOS Test Site Program facilities) for determination of the performance of profile retrieval algorithms and algorithms for land surface skin temperature (day/night), land spectral emissivity, land surface albedo, short-wave and longwave IR fluxes, as well as atmospheric properties, including cloud properties (including cirrus, stratus, and strong convective precipitating clouds). The seasonal variability of land cover and the dynamic range of the associated land products (albedo, fluxes etc.) requires that campaigns which adequately sample this annual variability be undertaken.

Consider the following table of possible observational periods and sites (note: many of these are currently planned by EOS and other agencies. The AIRS project is not proposing to underwrite the following scenarios, but expects detailed flight opportunities to be worked out September 1997 at the PM Validation meeting):

Table 2.5: Cloud Type versus Location/Time of Best Observation*

Cloud	WMO class	Possible Sites	Time of Max Occurrence	Scan Types
Cumulus (Cu)	Low	Florida Hawaii Tahiti	All year Summer Winter	NS,TT,S
Nimbostratus (Ns)	Mid	Arctic/Alaska Antarctic	Spring Spring	NS,TT,S
Cumulonimbus (Cb)	Low	Florida Philippines	Summer Summer	NS,TT,S
Stratus (St)/ Stratocumulus (Sc)	Low	NW US/AK W. S. Am	All year Summer-Fall	NS,TT
Cirrus (Ci)/ Cirrostratus (Cs)/ Cirrocumulus (Cc)	High	NW US Alaska E. US S. Mexico	Winter Summer Winter Fall	NS,TT,S
Altostratus (As) Altocumulus (Ac)	Mid	N Pacific Alaska S. Mexico	Spring Spring Summer	NS,TT,S

* Data from Hahn, Warren and London

Ground truth
1) Cloud/moisture LIDAR (if available)
2) Radiosondes
3) GOES Images

Supporting Aircraft
1) IR/VIS Imager (needs channels sensitive to water vapor)
2) Some Microwave instruments could be valuable but not critical

Table 2.6 Land Surface (cloud free conditions only)

Condition Type	Possible Sites	Season	Scan types
Desert/Semi-arid	White Sands, NM	Any	NS,TT,S
Grasslands	Wyoming	Spring/Fall	NS,TT,S
Forest	Alaska (SAR)	Summer	NS,TT,S
	Michigan (BOREAS)	Spring-Fall	
Vegetation	Mississippi Basin	Spring-Fall	NS,TT,S
	ARM/CART Site	Spring-Fall	

Ground truth

1) Ground geology/vegetation index
2) Radiosondes

Supporting Aircraft

1) IR/VIS Imager (needs channels sensitive to water vapor and IR window)
2) Some Microwave Imager (Passive or Active) could be valuable but not critical

Table 2.7 Spectroscopy (ocean/lake, cloud free conditions only)

Condition Type	Possible Sites	Season	Scan types
Wet/Hot	Gulf of Mexico	Spring-Summer	NS, TT
	Florida		
	Tropical Western Pacific (ARM)		
Wet/Cold	Alaskan North Slope (ARM)	Spring/Fall	NS, TT
Dry	SW lake / Ocean	Early Winter	NS, TT

Ground truth (very critical)

1) Radiosondes (CLASS Sondes if available)
2) water vapor LIDAR
3) cloud LIDAR (if available)
4) buoys
5) GOES Images/Local forecast information

Supporting Aircraft

1) IR spectrometer (HIS, NAST-I, AES, HI - Harvard U. Interferometer) with high spectral resolution of CO_2 and H_2O regions. It is strongly preferred that this be on an ER-2.
2) IR/VIS imager with H_2O channels. LASE water vapor measurements.
3) Microwave imager/sounder is desired and useful for AIRS/AMSU-A comparisons
4) Additional aircraft H_2O remote sensing (LASE) is absolutely critical. This should either be co-incident (same aircraft -- best option) or with co-located (different aircraft -- better than nothing option) observations with the instruments in 1-3

Core Flight Campaign Summary (possible sites)

cloud flight segments

Cloud	WMO Class	Climatic Conditions/Area	Season	Scan Types	Applicable Campaigns	Applicable Instruments
Cumulus (Cu)	Low	Tropical - Florida - Hawaii - Tahiti	 All Year Summer Winter	NS, TT, S	CAMEX DOE/ARM (TWP) GEWEX (LBA) GEWEX (GAME) GEWEX (ISCCP)	NAST AES HI Cloud Profiling Radar Project
Nimbostratus (Ns)	Mid	Polar - Arctic/Alaska - Antarctic	 Spring Spring	NS, TT, S	GEWEX (ISCCP) GEWEX (BALTEX) GEWEX (GCSS) DOE/ARM (NSA) SHEBA	NAST AES HI
Cumulonimbus (Cb)	Low	Tropical - Florida - Philippines	 Summer Summer	NS, TT, S	CAMEX DOE/ARM (TWP) GEWEX (GAME) GEWEX (LBA) GEWEX (ISCCP) GEWEX (GCSS)	NAST AES HI
Stratus (St)/ Stratocumulus (Sc)	Low	NW U.S./Alaska W. So America	All year Summer-Fall	NS, TT	DOE/ARM (SGP) GEWEX (ISCCP) GEWEX (LBA) GEWEX (GCSS) GEWEX (SRB)	NAST AES HI
Cirrus (Ci)/ Cirrostratus (Cs)/ Cirrocumulus (Cc)	High	NW U.S. Alaska Eastern U.S. S. Mexico	Winter Summer Winter Fall	NS, TT, S	CAMEX DOE/ARM (NSA) GEWEX (BSRN) GEWEX (ISCCP) GEWEX (GCSS) GEWEX (SRB)	NAST AES HI
Altostratus	Mid	N. Pacific Alaska S. Mexico	Spring Spring Summer	NS, TT, S	DOE/ARM (NSA) GEWEX (BSRN) GEWEX (SRB) GEWEX (ISCCP) GEWEX (GCSS)	NAST AES HI

NAST = NPOESS Atmospheric Sounder Testbed ; AES=Atmospheric Emission Spectrometer ; HI = Harvard Interferometer

land flight segments

Land Surface Condition Type	Climatic Conditions/Area	Season	Scan Types	Applicable Campaigns	Applicable Instruments
Desert/Semi-arid	White Sands, NM Lunar Lake, NV Railroad Valley, NV Edwards AFB, CA Arizona	Any	NS, TT, S	GEWEX (SRB) GEWEX (ISLSCP) SALSA	NAST AES HI
Grasslands	Wyoming	Sprint/Fall	NS, TT, S	DOE/ARM (SGP) GEWEX (SRB) GEWEX (ISLSCP)	NAST AES HI
Forest	Alaska Michigan N.W. U.S.A.	Summer Sprint-Fall	NS, TT, S	DOE/ARM (NSA) GEWEX (SRB) GEWEX (ISLSCP)	NAST AES HI

	Canada			Harvard Forest - Temperate Deciduous Forest Site BOREAS Thompson Site	
Vegetation	Mississippi Basin S. America	Spring-Fall	NS, TT	DOE/ARM (SGP) GEWEX (SRB) GEWEX (LBA) GEWEX (ISLSCP)	NAST AES HI

NAST = NPOESS Atmospheric Sounder Testbed ; AES=Atmospheric Emission Spectrometer ; HI = Harvard Interferometer

Spectroscopic validation segments

Spectroscopy Condition Type	**Climatic Conditions/Area**	**Season**	**Scan Types**	**Applicable Campaigns**	**Applicable Instruments**
Wet/Hot	Tropical	Spring-Summer	NS, TT	DOE/ARM (TWP) GEWEX (LBA) AERONET	NAST AES HI
Wet/Cold	Alaska Canada	Sprint/Fall	NS, TT,	DOE/ARM (NSA) GEWEX (BSRN) GEWEX (SRB) AERONET	NAST AES HI
Dry	SW Lake /Ocean Land sites (TBD) White Sands/Night Lunar Lake, NV Railroad Valley, NV Edwards A.F.B., CA Arizona	Summer Spring-Fall	NS, TT, S	GEWEX (SRB) GEWEX (BSRN) AERONET SALSA	NAST AES HI

NAST = NPOESS Atmospheric Sounder Testbed ; AES=Atmospheric Emission Spectrometer ; HI = Harvard Interferometer

Microwave Sampling Requirements

The requirements are similar to those of AIRS except for the case of rain which effects the cloud clearing ability of the L2 retrieval algorithm. Rain has a higher spatial and temporal variability than the other atmospheric variables.

VIS Sampling Requirements

The two primary products of the VIS detectors are a low-cloud flag and a surface inhomogeneity flag. In addition to the field campaigns already discussed, there are other ground locations, not requiring fieldwork, well suited to validating these products. For the low-cloud algorithm, each WMO weather station can be considered a field site, since cloud type and amount is a standard report item, and low-clouds are reliably recognized. In addition, a handful of regions will be selected that, based on climatology or other data, are expected to have or not have low-clouds. Unusual values of the cloud flag over such regions will be checked for consistency with data from other instruments on the PM platform (AIRS-IR, MODIS) and with forecasts from operational weather models. Examples of regions commonly having low-clouds are Florida, Hawaii in the summer, the Philippines in the summer, the Pacific Northwest, and the California coast in late spring, early summer. Similarly, regions will be selected where the surface inhomogeneity flag is known to be false (oceans, White Sands) and true (San Francisco, Manhattan, mountain glaciers, and broken ice pack are possibilities). Anomalous returns from these regions will be investigated with all available co-located data, particularly AVHRR and MODIS images.

2.3 Success criteria

The two key success criteria for AIRS are the stability of measurements and measurement accuracy. Stability will be evaluated primarily by monitoring the calibration coefficients. Regarding accuracy, the primary success criteria for AIRS/AMSU-A/HSB is the tropospheric accuracy of temperature profiles of 1 K with a resolution of 1 km in the vertical. The main tool to validate this is the well established technique of radiosonde collocations with AIRS geophysical parameter retrievals. Because AIRS/AMSU-A/HSB produces retrieval with a much greater accuracy than its predecessor HIRS2/MSU, special radiosonde campaigns are being setup for better coincidence between matchup. These special campaigns are also very critical to the validation of water vapor because of the high spatial and temporal variation of that parameter.

3 Pre-launch Activities

AIRS pre-launch validation activities include spectroscopic and forward model validations using previous and future field campaigns, theoretical retrieval algorithm error characterization, and pre-flight instrument performance validation. We envision AIRS involvement in existing field campaigns to consist primarily of augmentation of existing flight programs and ground instrument complements. In particular, this may involve AIRS-specific flight plans and additional research grade radiosonde launches, as well as efforts to coordinate observations by specific instruments such as HIS and LASE. Prior to AIRS launch, this involvement will logically include the applicable EOS validation campaigns for the AM-1 platform. Also important are the study of existing data sets and a characterization of their statistical properties.

Ground Campaign Strategy

Given the large amount of current AM planning for EOS validation activities, the AIRS team feels that augmentation of currently existing flight programs is the most cost effective approach. Organization and planning are the keys to success, and will be started at the September 1997 PM validation meeting.

Ground Measurement Support

An essential element for a successful field experiment is sufficient and accurate in situ ground truth. There are many difficult problems associated with the use of in situ data, among them the intercalibration of ground support measurements and the use of point measurements to characterize a possibly noncoherent area average associated with a satellite measurement. To solve the first problem, an effort will be taken to insure rapid delivery and analysis of all the measurement platforms. The second can be tackled in one of two ways: (1) extensive ground measurement equipment, or (2) use of auxiliary aircraft measurements such as an IR/VIS imager to characterize subgrid scale inhomogeniety.

The types of ground support measurements needed are Radiosondes (preferably CLASS sondes), surface station (ground or ocean) measurements, water profile information of a higher caliber than radiosondes (LIDAR), cloud information (cloud LIDAR) and current NOAA forecast/satellite information. Other information such as ground emissivity and soil type measurements would be extremely valuable.

Available Campaign Instrument Packages for AIRS/AMSU-A/HSB

There are three possible ‘AIRS-like’ instrument candidates currently available and two future possibilities. The first is the High Resolution Interferometer Sounder (HIS), a University of Wisconsin Michelson interferometer which matches the AIRS spectral resolution and spectral coverage. A similar instrument has been built by Jim Andersons’ Harvard group which is also a Michelson interferometer. The third is the Atmospheric Emission Spectrometer (AES), a high spectral resolution infrared interferometer prototype for the Tropospheric Emission Spectrometer (TES). There also currently exist microwave instruments with characteristics which match AMSU-A and HSB.

One future possibility is the utilization of the AIRS engineering model built by LMIRIS and available in 1998 and beyond. Also, the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) is planning the NPOESS Atmospheric Sounder Testbed (NAST) which will consist of a scanning Michelson interferometer with similar characteristics as HIS and a scanning microwave instrument designed to accommodate the 54-GHz and 118-GHz oxygen bands They are expected to fly with the currently available 183-GHz water band sounder from the Goddard Space Flight Center and will be available in early 1998.

1. ER2/CAMEX Package

Previous flight experiments, the Convection And Moisture EXperiment (CAMEX 1&2) were carried out at Wallops Flight Facility (WFF). These experiments were an ideal testbed for an AIRS ground campaign. The ER2 was deployed from AMES and carried a suite of instruments. The relevant instruments for AIRS validation onboard the ER2 were the (1) HIS, as previously described; (2) Microwave Temperature Sounder (MTS) a MIT instrument equivalent to the AMSU-A; (3) Millimeter-wave Imaging Radiometer (MIR) a Goddard Space Flight Center (GSFC) water vapor instrument equivalent to the AMSU-B and (4) Multispectral Atmospheric Mapping Sensor (MAMS) a Marshall Space Flight Center (MSFC) broadband high spatial resolution IR and Visible imager. The proper alternative to MAMS would be the MODIS Airborne Simulator (MAS). In addition to the ER2 instruments there were surface instruments which are valuable for AIRS validation. These were: 1) GSFC Raman Lidar; 2) Ground Based HIS; 3) Rawinsonde balloon launches for GSFC Lidar, GB-HIS and ER2 overflights; 4) NOAA observation buoys. The disadvantage of the U of W HIS instrument is that it is a fixed-viewing only instrument and would be unable to perform the target tracking scan mode. The advantage of the ER2 package itself is the high altitude flight which allows the characterization of the Troposphere and the study of high altitude cirrus clouds.

2. <u>P3/AES Package</u>

The Air-borne Emission Spectrometer (AES) is a down-looking infrared Fourier transform spectrometer (FTS) designed to measure atmospheric emission in the 650 cm-1 - 4350 cm-1 spectral range with a resolution of better than 0.1 cm-1. The instrument is readily adapted to a variety of platforms and has flown on NASA's DC-8, P-3 and C-130Q. There is a CCD camera covering the AES FOV and the instrument is capable of operating in the joystick mode allowing target tracking. The spectral resolution is approximately 10 times greater than AIRS and would be ideal for the characterization of spectral surface and cloud emissivities as a function of angle and would enhance the spectroscopic validation effort. The drawback to the AES package is the relatively low altitude of the aircraft and unknown auxiliary payloads.

3. <u>Harvard/Anderson FTS (HI)</u>

This is a scanning infrared Michelson interferometer flying on an ER2 with a large array of onboard in situ devices. Its maiden flight occurred August 1997. One of the main goals of this package is the measurement of upper troposphere water vapor, a critical need for AIRS. The device also has the unique ability to look up to enable observation of the upper tropospheric water without the lower tropospheric background.

3.1 Spectroscopic Validation

Spectroscopic validation refers to the molecular physics that goes into a line-by-line transmittance/radiance algorithm. Spectroscopic validation includes (a) laboratory measurements and analysis of spectra that are not sufficiently well known for AIRS applications, (b) field measurements of atmospheric spectra that cannot be adequately characterized in the laboratory (generally due to insufficient optical depths in the lab) that will be used to improve our spectroscopic models, and (c) field measurements of atmospheric spectra to validate our existing spectroscopic models in the real atmosphere. (b) and (c) are related, but (b) is much more demanding in that we assume that in-situ measurements of the atmospheric state are more accurate than the spectroscopy we are trying to measure.

The following sub-subsections discuss the particular spectroscopic issues that need to be addressed prior to AIRS launch. In a following section we propose an observation strategy for new field campaigns to address these issues. Were applicable, existing datasets from previous field campaigns will also be used to address these issues. AIRS observations of water vapor will potentially be more accurate than radiosonde measurements, especially in the upper troposphere (Strow, 1997b). This puts a premium on accurate spectroscopy for water vapor, especially the continuum, which cannot be generated from a few spectroscopic parameters and must be modeled empirically using as many laboratory/field measurements as possible, under widely varying conditions.

3.1.1 H_2O Continuum

Two of the key spectroscopic issues to be addressed before AIRS launch are the proper modeling of the H_2O continuum and the dominance of self or foreign broadening in different spectral regions. Recent laboratory work and modeling by Tobin and Strow [Tobin 1996a, Tobin et al., 1996b] has improved our ability to correctly calculate the 1400-1800 cm-1 H_2O continuum when compared to the best validated HIS observations. However, the change in H_2O continuum dependence from Pressure $(H_2O)^2$ to Pressure (H_2O) occurs in the 1300-1400 cm-1 region, requiring new, longer path laboratory work for accurate parametrization. This new lab work can be performed at Rutherford Appleton Lab (RAL) in the United Kingdom using their high resolution Fourier spectrometers which is tightly coupled to a stainless steel long-path multi-pass cell capable of up to 500 meters pathlength. In addition, RAL can perform needed low temperature measurements of the H_2O continuum in the stronger portion of the water band. This will enable modeling of the temperature dependence of the H_2O continuum for the upper tropospheric AIRS channels above 1400 cm-1. Derived improvements to the H_2O continuum will be verified with both up-looking (Atmospheric Emitted Radiance Interferometer -- AERI and high resolution AERI-X) and down-looking (HIS, etc.) for campaigns with extremely uniform conditions and co-located in-situ sensor.

3.1.2 Upper Tropospheric H_2O

While the new H_2O continuum and lineshape model (Tobin et al, 1996b) provides an improved calculation in between H_2O lines, our best calculation of a HIS spectrum is still in error on the strong water lines by up to 3-5K, an order of magnitude higher than the level we expect from known uncertainties in line-strengths and continuum. We believe these line center errors are due to radiosondes systematically reporting too dry conditions in the upper troposphere. Confirmation of this radiosonde bias with high-quality in situ (frost-point, lyman-alpha hygrometers) and validated remotely sensed H_2O from aircraft based LIDAR (LASE) and spectral remote sensing observations (HIS/NAST-I/AES/HI) from coordinated field campaigns will help validate the AIRS global upper troposphere H_2O product, since it cannot be done with radiosondes alone. Such coordinated and validated observations should be a major goal of any future field campaign with which AIRS is involved. Understanding this atmospheric region is critically important to improving global climate modeling (transport of tropospheric water into the upper troposphere) and our understanding of stratospheric chemistry.

3.1.3 CO_2 Lineshapes

Additional in situ/remote sensing campaigns/IOPS will also provide the necessary validation of models of line-mixing and far-wing lineshape for CO_2 in both the 15 and 4.3 micron spectral regions. These spectroscopic improvements are necessary for AIRS to retrieve accurate temperature profiles and investigate the increase in atmospheric CO_2. Derived improvements to CO_2 P/R line-mixing should be verified with both up-looking (AERI-X) and down-looking (HIS, etc.) IR spectra from previous and future field experiments. This work should not require special in-situ instrumentation other than co-located radiosondes and uniform atmospheric conditions, and as such are less demanding than validation of water vapor spectroscopy.

3.2 Forward Model Validation

Forward model validation tests (a) the fast parametrization of the spectroscopy in the form of the AIRS fast transmittance algorithm (Hannon et al., 1996, (b) the fast radiance algorithm that uses these fast transmittances, (c) the instrument spectral response function used in (a), and (d) the computer codes used in a-c. The AIRS Radiative Transfer Validation Model (RTVM) is the link between line-by-line codes and the fast forward radiance model.

The clear-air radiances produced by the AIRS RTVM will be based on kCARTA, a new monochromatic algorithm for computation of atmospheric transmittances and radiances that utilizes compressed look-up tables (Strow et al., 1997a). kCARTA is 10+ times faster than standard line-by-line algorithms and much easier to use. It is validated with a combination of the GENLN2 line-by-line code and other more specialized codes used to analyze and model laboratory spectra. We use kCARTA to compute the convolved layer-to-space transmittances that are used to generate the AIRS fast transmittance model parameters. kCARTA is also used for the calculation of observed HIS radiances when in-situ data is available. Consequently, kCARTA is the vehicle for both spectroscopic validation using aircraft radiances and generation of the AIRS fast transmittance algorithm.

3.2.1 AIRS RTVM Validation

A key theoretical tool for validating the AIRS/AMSU-A/HSB radiance measurements and the retrieved products is a complete forward model which allows for accurate calculations of AIRS spectral radiances from surface and atmospheric composition variables and solar geometry. The forward model must include all the physical variables and processes regulating the transfer of surface and atmospheric radiance to space over the complete spectral range of the AIRS/AMSU-A/HSB system and for the appropriate spectral response characteristics. A number of pre-launch field campaigns presently are contributing valuable data sets which are guiding approaches to the AIRS validation activity; in particular, they are permitting the testing and refining of appropriate methods and techniques and providing estimates of associated error budgets. In particular, CAMEX I and II, FIRE II, OTIS and SUCCESS are examples of campaigns that have made a valuable contribution to this exercise. A sequence of new field experiments over the years 1997-2000 should enhance the pre-launch program. The physical variables include (as described in eqn 2.12 and 2.13) :

- Surface skin temperature
- Surface emissivity/reflectivity, including its dependence on surface type, roughness, etc.
- Atmospheric temperature
- Atmospheric water vapor
- All radiatively active trace gases (i.e., CO_2, O_2, O_3, CH_4, N_2O, CO, etc.)
- Aerosols, including their dependence on humidity, and
- Clouds, including their geometrical and microphysical properties.

The physical processes to be included are:

- Surface emission and reflection
- Atmospheric absorption/emission/scattering
- Aerosol absorption/emission/scattering
- Cloud absorption/emission/scattering
- Solar radiation absorption/emission/scattering

all of which are to be dependent on the microphysical characteristics of the radiatively active medium. The Radiative Transfer Validation Model (RTVM) will be as computationally exact as is practically possible making use of line by line (LBL) atmospheric absorption models, multiple scattering theory, and methods to account for irregularly shaped cloud and aerosol particles. Several hundred atmospheric levels and exceedingly high spectral resolution ($\lambda / \Delta\lambda > 10^6$) will be used to minimize errors in numerical quadrature. Although a single radiative transfer calculation may take an hour or more on a state of the art workstation, this is not felt to be a serious limitation for a validation algorithm since the number of cases in the validation data set will be quite limited. Requirements for physical completeness and numerical accuracy are much more important than computational efficiency. The RTVM will be applied to AIRS/AMSU-A/HSB-observation-coincident validation data sets achieved from aircraft, ground sites, and satellites, for independent validation of the AIRS/AMSU-A/HSB spectral radiance observations. The RTVM will also be applied to retrieved surface and atmospheric parameters to check the internal radiative consistency of the retrieved products with the radiance observations. This validation process is expected to provide an adequate assessment of the accuracy of the AIRS/AMSU-A/HSB measurement, retrieved products, and the retrieval algorithms, as well as the uncertainties of the accuracy estimates due to errors in the state variables, atmospheric variability, and the accuracy of the radiative transfer validation model. An important objective is to isolate a source of error (i.e., measurement and/or modeling) and to provide sufficient information to alleviate it so as to improve the accuracy of AIRS system products.

Validation of the AIRS/AMSU-A/HSB radiances is a two step process: validation of the RTVM line-by-line (LBL) model with observations, and subsequent use of the LBL model in the RTVM to compare with the AIRS observations. A key requirement is the accurate determination of the atmospheric transmittance profile by the LBL forward model. This, in turn, requires that the atmospheric state used in the LBL calculation be representative of the atmosphere in the AIRS FOV. The LBL model radiances are then directly compared to coincident radiance measurements by instruments of which the calibration and characteristics are well understood. The majority of the focus will be on the infrared radiances because of the direct impact on the sounding accuracy.

To achieve the necessary accuracy in measurement of the various atmospheric parameters, a combination of in-situ and remotely sensed data is required. This will involve the regular release of research grade radiosondes (temperature, water vapor, and ozone), the use of a Raman LIDAR system with a tethersonde (boundary layer water vapor), HIS/NASTI measurements (upwelling radiance, upper level temperature and water vapor retrievals), and the AERI (downwelling radiance, boundary layer temperature and water vapor retrievals). A LIDAR system for definition of aerosol extinction and backscatter properties with altitude will be necessary when high aerosol optical thickness prevail.

The data provided by the above complement of instruments will provide information of the atmospheric state below the ER-2 aircraft. For opaque regions of the IR spectrum, such as the 15μm CO_2 region, the atmosphere above the aircraft must be characterized by some other means. Experience with the GOES-8 (van Delst, 1996, *pers. com.*.) has shown that incorrect representation of the shape, not magnitude, of the stratospheric temperature profile can have a 3-4 K impact on the opaque channel calculated brightness temperatures. In this case a combination of numerical model and independent upper atmospheric data (such as currently might be derived from UARS, TOVS/SSU retrievals) may be used to adjust climatological profiles. Another important aspect of defining the atmospheric profile in the LBL model for opaque channels is the vertical resolution of the temperature profile data. HIS results have shown that the magnitude of on-line absorption in the 15μm CO_2 region agrees much better with observations when there is a well defined temperature profile in the tropopause-to-aircraft (approximately 100-50 mb) atmospheric layer.

3.2.2 AFM Validation

It will be difficult to <u>completely</u> validate the AIRS fast forward model before launch with field campaigns since, in principle, all layer transmittances in the fast model depend on the atmospheric state in all layers above the one under consideration. This problem is an artifact introduced by the use of effective convolved layer transmittances, instead of computing monochromatic transmittances and then convolving the observed radiances with the instrument function. Consequently, radiances measured at ER-2 altitudes (50 mbar), cannot always be adequately simulated with the actual AIRS fast transmittance model. Clearly, for channels that peak very low in the atmosphere, this will not be a problem. However, channels with weighting functions that peak in the mid-troposphere can often have significant components at altitudes above 50 mbar. For these reasons, validation of the AIRS forward radiance model (not spectroscopic validation, or validation of the AIRS RTVM) will have to be performed after launch.

3.3 Field Campaigns

Prior to AIRS launch, datasets from previous and ongoing/future field campaigns will be used for spectroscopic and forward model validation. As defined here, previous field campaigns refers to any campaign prior to the publication of this document. Thus, ongoing/future pre-launch campaigns refers to any campaign that is currently ongoing, or planned to occur between now and AIRS launch. The uses of these datasets has been previously described in sections dealing with spectroscopic and forward model validation. Here, we will give a brief outline of what measurements have been made in the past, what instrument capabilities will be of used to AIRS, and a proposed observing strategy to enhance future field measurements to produce measurements required for AIRS pre-launch validation.

3.3.1 Previous Field Campaigns

AIRS participated in the First and Second Convection And Moisture Experiments (CAMEX1 -- September 1993 and CAMEX2 -- August/September 1995) with specific flights flown to produce some of the data needed for pre-launch spectroscopic and forward model validation. These experiments were based at NASA's Wallops Island Facility and were an ideal testbed for an AIRS ground campaign. An ER-2 was deployed with a suite of instruments useful for AIRS validation: (1) HIS (previously described), (2) the MIT Microwave Temperature Sounder (MTS) equivalent to AMSU-A, (3) the GSFC Millimeter-wave Imaging Radiometer (MIR) equivalent to AMSU-B, and (4) the MSFC Multispectral Atmospheric Mapping Sensor (MAMS) a broad-band high spatial resolution IR and Visible imager. In addition to the ER-2 instruments, the following surface instruments valuable for AIRS validation were used: (1) GSFC Raman LIDAR for H_2O and aerosol profiles in the lower-middle troposphere, (2) the University of Wisconsin's up-looking interferometer (AERI), (3) Rawinsonde balloon launches from both the GSFC facility, and the University of Wisconsin CLASS system, (4) NOAA observation buoys for sea surface temperatures.

While CAMEX1 and CAMEX2 produced some invaluable data, they also point out the difficulties involved in field campaign validation measurements. Great care must be taken to get coordinated in situ and ground remote sensing measurements with aircraft remote sensing observations. This is particularly true of radiosonde profiles which do not occur at a single point, but along the track of the balloon as it moves at the mercy of the winds. Great care must also be taken to make the validation measurements during periods of uniform atmospheric conditions, and over water for lower-mid tropospheric spectroscopy. And of course, several flights should be flown to allow for instrument operation problems. All of these issues are addressed in the proposed observing strategy for future campaigns discussed in a following sub-subsection.

In addition to CAMEX1 and CAMEX2, other previous field experiments have produced some data useful for AIRS validation including the FIRE II (Nov/Dec 1991), OTIS (Jan 1995), SUCCESS (April/May 1996) campaigns and the boundary layer water vapor IOP at the DOE ARM CART site in Lamont, Oklahoma in September 1996. We will continue to examine the datasets from these campaigns for there use in AIRS validation activities.

3.3.2 Existing Instrument Capabilities

A suite of airborne and surface instruments will be required for future AIRS validation activities as described in the following sub-sub-subsections.

Ground-Truth Instrument Support

An essential element for a successful field experiment is sufficient and accurate in situ and remote sensing ground truth. There are many difficult problems associated with the use of in situ data, among them the inter-calibration of ground support measurements and the use of point measurements to characterize possible inhomogeneous area average associated with a satellite measurement. To solve the first problem, we will use well maintained instruments with a documented capability of making good measurements and working with other instruments for inter-calibration and will make every effort to insure rapid delivery and analysis of all the measurement data. The second can be tackled in one of two ways: (1) extensive ground measurement equipment, or (2) use of auxiliary aircraft measurements such as an IR/VIS imager to characterize sub-IR grid scale inhomogeneities. In addition to the actual ground-based instruments, a variety of airborne in situ and remote sensing instruments will be required along with NOAA forecast/satellite information.

Ground-based Instruments

(1) Surface station (ground or ocean) with temperature, humidity, winds.

(2) LIDAR (Raman or other) for H_2O (better than sonde) and aerosol profiles in the lower-middle troposphere.

(3) Up-looking microwave radiometer for total column H_2O.

(4) Up-looking IR interferometer or spectrometer for high resolution spectral measurements for spectroscopic validation.

(5) Cloud LIDAR for cloud altitude and thickness.

Airborne Instruments

(1) Radiosondes, preferably CLASS systems and preferably either multiple launches on one balloon or from multiple sites for better characterization of conditions and sonde errors.

(2) Ozonesondes for direct measurement of Ozone profiles.

(3) Superior aircraft in situ H_2O (frost-point hygrometer?), particularly in the upper troposphere where radiosonde H_2O measurements are unreliable.

(4) Aircraft in situ of IR active trace gases

(5) Airborne LIDAR (LASE) for upper tropospheric H_2O and aerosol profiles.

Airborne "AIRS/AMSU-A/HSB" Instrument Packages

There are three possible "AIRS-like" instrument packages available and three future possibilities. The first is the University of Wisconsin HIS, a Michelson interferometer which matches AIRS spectral resolution and coverage. A similar interferometer (HI) has been built by Jim Anderson's group at Harvard. The third is the Atmospheric Emission Spectrometer (AES), a high resolution IR interferometer prototype for the Tropospheric Emission Spectrometer (TES).

As previously discussed in 3.3.1, there already exist microwave instruments similar to AMSU-A and HSB. The MIT Microwave Temperature Sounder (MTS) is equivalent to AMSU-A, while the GSFC Millimeter-wave Imaging Radiometer (MIR) is equivalent to AMSU-B thus sharing characteristics with HSB.

One of the future "AIRS-like" instruments is the possible utilization of the AIRS engineering model built by LMIRIS and available in 1998. The other two future "AIRS-like" instruments are both cross track scanning interferometers somewhat derived from HIS. The Scanning HIS (SHIS) is expected to fly in late 1997 and is similar in design to HIS but with a cross-track scanning capability. The other is the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Atmospheric Sounder Testbed (NAST) expected to fly in early 1998. NAST consists of a cross-track scanning Michelson interferometer similar to HIS and a cross-track scanning 54-GHz and 183-GHz microwave instrument.

As discussed in 3.3.1, HIS, MTS, and MIR have flown previously on the ER-2 during CAMEX1 and CAMEX2. It is likely that HI and NAST also can fly on the ER-2 with MTS and MIR depending on space and weight limitations. The high altitude of the ER-2 allow characterization of the entire troposphere including upper tropospheric H_2O and the study of high altitude cirrus clouds. The cross-track scanning of NAST and SHIS are very advantageous over the nadir only viewing geometry of HIS. However, HIS has a long flight heritage and we have already made extensive use of HIS data. Unfortunately, AES is restricted to the C-130, P-3, and DC-8. Although AES's higher spectral resolution (10x AIRS) would be ideal for characterizing spectral surface and cloud emissivities as a function of angle, it's restriction to low altitude aircraft and unknown auxiliary payloads are significant drawbacks. It may be of some use for spectroscopic validation, but signal to noise and low altitude are serious concerns.

3.3.3 AIRS Observing Strategy for Future Field Campaigns

In order to deliver the best possible AIRS Fast Forward Model by the time of AIRS launch scheduled for December 2000, a well validated dataset of field measurements should be obtained in the next 1-2 years. We envision AIRS involvement in future field campaigns to consist primarily of augmentation of existing flight programs and ground instrument complements, not separately funded AIRS validation campaigns. In particular, this may involve AIRS specific flight plans and additional research grade radiosonde launches, as well as efforts to coordinate observations by specific instruments such as HIS and LASE. Prior to AIRS launch, this involvement will logically include the applicable EOS validation campaigns for the AM-1 platform.

Two currently planned field campaigns are of particular interest to AIRS due to their timing, location, and complement of instruments. As currently planned, CAMEX3 will take place in August and September 1998 with aircraft based at Patrick AFB in Florida and a probable ground site on Andros Island in the Bahamas and a focus on hurricane development, intensification, tracking, and landfall in the western Atlantic, Caribbean, and Gulf of Mexico. This will be a coordinated effort of NASA funded ER-2 and Dc-8 flights and NOAA and USAF hurricane operational and research aircraft. A similar complement of instruments is expected for the ER-2 and the ground site as was used in CAMEX1 and CAMEX2. NASA DC-8 instrumentation will include the NASA-Langley LASE airborne DIAL Lidar operating in both up- and down-looking modes. CAMEX3 flight activities will be coordinated with the National Weather Service and USAF hurricane hunter aircraft offering in situ temperature and H_2O measurements at flight level and dropsonde profiles below the aircraft. While CAMEX3 will be focused on hurricanes, there is a high likelihood for significant validation data. Given the timing and complement of instruments involved in CAMEX3, it is highly desirable that AIRS coordinate with CAMEX3 planning to obtain 3-5 dedicated validation flights. The FIRE III field campaign scheduled for the Arctic region in 1999 is useful for its timing before AIRS launch and location to provide high latitude observations.

<u>Field Campaign Locations</u>

To simultaneously validate both upper and lower troposphere H_2O, a site over open ocean would provide the best location for H_2O campaigns/IOPS. Extremely uniform conditions over large spatial areas and clear skies are required. A site in the tropics would provide useful observations of high column H_2O atmospheric conditions. Satisfactory conditions could be found in the central Gulf of Mexico or in the Caribbean, with surface instruments based on a ship or small island. A ship provides mobility and ease of locating surface instruments in the open ocean. An island offers a convenient base of operations, but care must be taken to minimize the local effects of the island on remote observations (local weather effects, topographic effects, daytime heating, warming of shallower waters, etc.). The central Gulf of Mexico or Caribbean are also easily accessible areas for over-flights of aircraft with in situ and remote-sensing instruments. Prior to launch, data from at least one other site is highly desirable, preferably a cold, dry over ocean site.

Note, the need for uniform conditions over large spatial areas could conflict with the objectives of other investigators participating in ER-2 campaigns. Thus, every effort should be made to dedicate at least 3--5 flight days solely to AIRS H_2O validation.

While an open ocean site is required for lower tropospheric H_2O spectroscopic validation, upper tropospheric H_2O validation could occur over land. Measurements over the ocean provide a uniform scene, important for the portions of the H_2O band that originate in the lower troposphere and are sensitive to thermal emission from the surface. However, in the more opaque regions of the H_2O band, the radiation originates above 600 mb and is insensitive to the surface.

Instrumentation

A variety of surface, in situ, and aircraft/spacecraft instrumentation is required to meet the observing objectives. Surface-based sensors provide high quality information on the temporal variability of H_2O and, coupled with wind information, the spatial distribution of H_2O. The in situ sensors provide calibration points for both the up-looking surface and down-looking aircraft/spacecraft instruments. Down-looking aircraft remote sensors simulate AIRS observations and provide additional atmospheric state information.

Surface Instrumentation

Surface instrumentation should include, at least, a DIAL or Raman LIDAR H_2O profiler, a passive microwave H_2O sounder, an up-looking IR spectrometer, a GPS receiver, and some advanced in situ H_2O sensors. Preferably, the in situ H_2O sensors would be located on a tower to provide at least a small vertical range of measurements for comparison/calibration of the LIDAR, microwave, IR spectrometer, and radiosonde systems. Conducting most observations at night will enable the LIDAR systems to provide more accurate H_2O profiles to higher altitudes. The LIDAR systems offer excellent vertical and temporal resolution throughout the observation period up to 8--10 km. The microwave system provides high temporal resolution information on the total H_2O content. The up-looking IR spectrometer provides high spectral, vertical (up to ~2 km), and temporal resolution of both temperature and H_2O (as well as other trace gases).

Radiosondes

Throughout a campaign/IOP, research grade radiosondes should be launched at regular intervals (at least twice daily). During aircraft flight days, radiosondes should be launched at least every 3 hours, more frequently where possible. These launches should be from multiple sites along the flight track, and, where possible, with multiple radiosondes on the same balloon. This will provide the best opportunity to, in detail, evaluate the quality of radiosonde measurements and look for any statistical biases. If an open ocean location is used, multiple ships might be required for the multiple radiosonde launches.

Aircraft In Situ

In addition to the radiosonde in situ H_2O profiling, high quality in situ H_2O measurements from instrumented aircraft are necessary. One or more aircraft profiling from 0 to at least 40,000 ft (0--13 km, 1000--200 mb) are required. It is known that radiosondes generally underestimate the abundance of H_2O in the cold upper troposphere above ~ 300 mb. Excellent in situ measurements in this region are critical to validating AIRS spectroscopy and forward models for the strongest H_2O lines. Radiosondes often have calibration offsets in the lower troposphere, thus good quality in situ measurements are also needed there. The aircraft in situ measurements also offer a common calibration point for ground-based H_2O profilers (LIDAR) and aircraft/spacecraft based remote observations (LIDAR and IR sounder). An additional in situ H_2O sensor on the ER-2 flying at ~ 60,000 ft (20 km, 50 mb) is also desired to fully model the lower stratosphere for ER-2/spacecraft remote observations.

Aircraft Remote Instrumentation

The primary remote sensing aircraft for AIRS pre-launch H_2O validation would likely be the NASA ER-2 with a suite of instruments. Only the ER-2 can provide observations of the high altitudes necessary to address the full range of H_2O spectroscopic issues. In addition to the above mentioned in situ H_2O sensor, ER-2 instrumentation should include, at least, a high spectral resolution IR sounder, a visible/IR imager, a microwave H_2O sounder, a LIDAR H_2O profiler, and perhaps a LIDAR cloud-top profiler. One choice for the IR sounder is the University of Wisconsin HIS. It has flown numerous times on the ER-2 and data from HIS has been used in previous H_2O spectroscopic validation studies. The microwave sounder combined with HIS provides a compliment similar to the AIRS/AMSU-A combination. Even better would be to fly the NAST instruments consisting of a high spectral resolution, scanning IR interferometer and advanced scanning microwave radiometer. NAST is expected to be available in 1998, perhaps in time for a pre-AIRS validation campaign, certainly in time for post-launch validation activities. MAS is similarly a good choice for the visible/IR imager. MAS has successfully flown before with HIS, and can likely fly with NAST. The clear choice for the LIDAR H_2O profiler is the NASA Langley LASE instrument. It too has ER-2 experience, but has never flown with HIS. Such co-incident observations with HIS/LASE or NAST/LASE would be invaluable to addressing H_2O spectroscopic issues, particularly in the upper troposphere where in situ measurements are difficult to make. Using LASE on a series of strong H_2O lines should provide high quality H_2O profiling from 10--20 km. This would provide excellent overlap with both the ground-based LIDAR and aircraft in situ. The cloud top profiler is less critical, since NAST, HIS, LASE, and MAS should provide information on the presence of clouds. However, at night, the MAS visible channels will not be as useful.

Operations Plan

Three to five dedicated flights of the ER-2 for H_2O validation during the campaign/IOPS are strongly desired to assure the acquisition of the required data. One or two over-flights of the surface site (ship or land) at the end of a few ER-2 flights most likely will not be sufficient. The most uniform cloud-free conditions are required, with every flight having the largest possible number of passes over open ocean at the surface site. The maximum number of radiosonde launches during an ER-2 flight is desired to obtain the best overlapping coverage of all portions of the atmospheric profile. To maximize coincidence, where possible, the ER-2 flight legs should be arranged along the primary atmospheric wind vector directly in line with the radiosonde trajectory. Similarly, the additional aircraft involved should fly along the same track as the ER-2. For many other concerns, these no doubt sound like the most boring possible flight plans. But, they are precisely what are required for good spectroscopic validation we desire for AIRS.

Clearly, locating the surface instruments/radiosonde launch site on a ship maximizes the flexibility of arranging aircraft flight legs along the radiosonde trajectory and over open ocean. An island location for the surface site places more constraints on the coordination of aircraft flight legs to stay over open ocean. However, atmospheric conditions in the tropics could be uniform enough that exact coincidence of radiosonde trajectory and aircraft flight legs are not as necessary. Cost and other logistical factors may dictate the base of surface operations.

3.4 Algorithm Error Characterization

The current TLSCF software has a full level 0 to level 2 data product simulation (spacecraft bits to radiances) with three goals in mind: (1) core algorithm performance is based on the simulation, (2) robustness testing of the AIRS data product algorithms is based partly on simulation, (3) data product validation requires an extensive simulation effort. The simulations are to be as realistic and challenging as possible as well as extensive enough to provide a complete set of exception conditions. The full physics, as described in 2.1.3, is used in generating the AIRS/AMSU-A/HSB radiances. The components in the AIRS simulation are described in Figure 3.1.

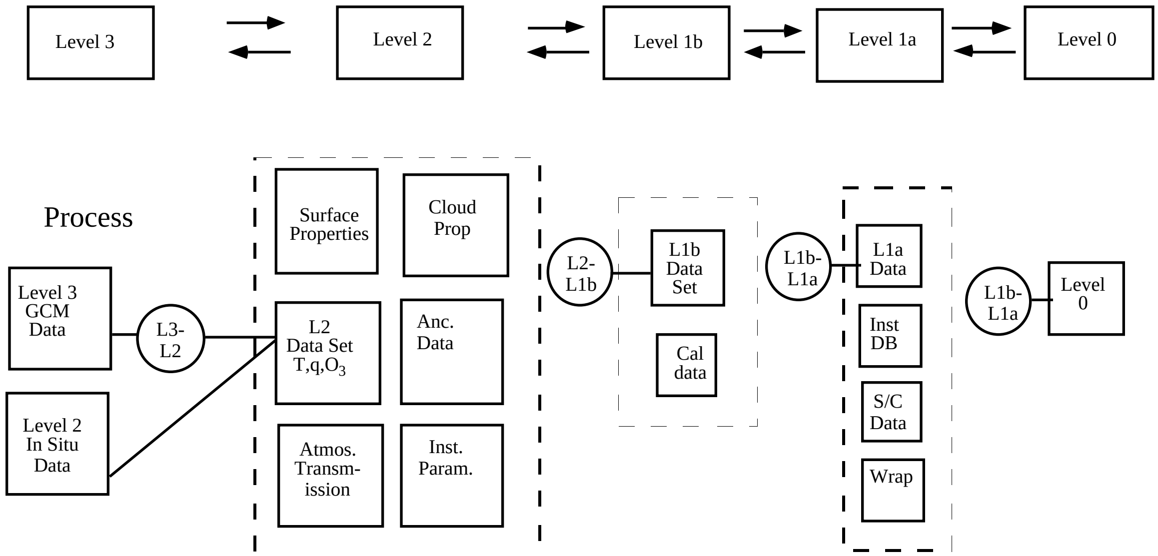


FIGURE 3.1: AIRS SIMULATION SYSTEM

This discussion will focus on the simulation of level 2 data:

1. The geophysical data are generated by team members at NOAA's National Centers for Environmental Prediction (NOAA/NCEP) using experimental mesoscale models. The model used for the current simulation comes from the forecast for July 1, 1993. It covers about 3080 km in longitude, 4700 km in latitude with a 40 km spacing grid, and is centered on the western part of the United States. At every grid point the model lists the temperature, water vapor, and fractional cloud cover as functions of pressure between 30 mb and the surface. These data are called Level 2 geophysical data by EOS. Also on-line are global models at a somewhat coarser horizontal resolution.
2. The simulation team selects satellite tracks from the mesoscale model and converts them to the radiances (level 1B) which the AIRS (IR/VIS), AMSU-A and HSB instruments would observe. All important instrument-related effects, such as detector noise, gaps in the spectral coverage, wavelength, and the spectral response function of each channel, are included in the calculations of the Level 1 data.

The simulation is one methodology to provide theoretically-based estimates of parameter space errors. For example, given a one degree error in temperature, how does this effect the accuracy of, say, the ozone retrieval. Also, the simulation can be used to provide estimates based on formal error propagation analysis.

3.5 Creation of Field Campaign Retrieval Test Data Sets

The simulation data sets to be used for team retrieval algorithm validation will be generated before the first validation field experiment. These data sets will be collected/generated as close to “in-situ data” as possible to ensure a successful validation exercise. For example, Level-2 data should be adapted from the traditional radiosonde instrument, deployed during previous experiments, and that will be used in the AIRS validation campaign. In the generation of such simulation sets radiosondes, (e.g. CLASS sondes) should be used for temperature and water vapor profiles, AVHRR data used for cloud fractional coverage, LIDAR data for cloud height, etc. In the case of large volumes of training data sets required for the initial state generation, climatological sets of radiosonde data will be used. The geographic location for these data sets can be selected according to the planned "first AIRS validation experiment." In this case, the simulated data sets can be tested using simulated AIRS-like Level-1 data, as well as the real AIRS-like Level-1 data collected during the validation.

The generation of simulation data sets require the use of RTVM of AIRS or AIRS-like instruments. Instrument noise together with the Level-2 data base (profiles), cloud heights (obtained from high resolution AVHRR/GOES infrared data) and cloud fractional coverage (obtained from AVHRR/GOES visible/infrared imager) are required. All these data should interpolate to the spatial resolution afforded by the particular altitude of the instruments in orbit or flight. The training data base should be generated in the same way using the historic Level-2 data in the same geographical area that will be used for post-launch AIRS validation.

Experimental data sets acquired from the NASA ER-2 during field campaigns will play a key role in providing experimental AIRS-like radiance data for testing retrieval algorithms prior to the launch of the EOS-PM spacecraft. In particular, the High spectral resolution Interferometer Sounder (HIS), the MODIS Airborne Simulator (MAS), the Microwave Temperature Sounder (MTS), and the Millimeter Imaging Radiometer (MIR) will provide data from the ER-2 flight altitude of 20 km which closely resembles the data to be achieved by the AIRS/AMSU-A/HSB and MODIS instruments aboard the PM satellite. Numerous data sets are now available for a variety of surface, meteorological, and cloud conditions where excellent surface and air "truth" validation measurements are available. Beginning in 1998, a new spatially scanning infrared interferometer and microwave sounding radiometer system, called NAST (NPOESS Aircraft Sounder Testbed) will be available for flight aboard the ER-2 and aircraft such as NCAR's WB-57. The NAST Interferometer (NASTI), with its spatially scanning capability with 2 km spatial resolution and 0.2 cm^{-1} spectral resolution, will be used to provide a very precise simulation of the AIRS radiance data that will be achieved from the PM orbit. In this case, the 2 km NASTI data will be spatially convolved, using the AIRS spatial response function, and spectrally convolved, using the AIRS spectral response function, to provide a data set for validation of the radiative transfer physics, cloud clearing, and parameter retrieval algorithms prior to the launch of the PM spacecraft. Flying along with NASTI will be the AIRS-compatible microwave component (NASTM). Ground truth will be provided both externally (i.e., ground-based remote sensing and in-situ surface and radiosonde measurements) as well as internally from full physics solutions (i.e., using the RTVM and RAVM discussed above) with the full spatial and spectral resolution of the NAST measurements. There is also a complimentary microwave instrument on the NAST platform which will be utilized for complete testing of the AIRS/AMSU-A/HSB suite of instruments.

In order to provide an empirical test of AIRS retrieval physics, the aircraft radiometric data will be prepared for team members' use for a variety of surface and atmospheric situations where excellent independent ground truth is available. The CAMEX I and II, FIRE-II, OTIS, and SUCCESS field campaigns are excellent examples for use of the existing HIS/MTS/MIR measurements for this purpose. Future ER-2 missions, some of which will include the NAST, will be conducted over DOE ARM ground-truth sites in Oklahoma and the North Slope of Alaska; these will provide additional unique experimental data sets for validating and improving AIRS retrieval physics prior to launch. One most important aspect of this process involves the impact of clouds on the AIRS retrievals. Since both HIS and NASTI achieve a 2 km spatial resolution, clear air "truth" is available for 15 km AIRS resolution footprints for most partially clouded situations. The clear-air truth radiance spectrum will be extremely valuable for validating and improving cloud clearing methodology and/or performing retrievals directly from cloud attenuated radiance measurements. Retrievals from the 2 km clear air radiances provide validation for products achieved from the lower spatial resolution AIRS-like radiances.

Tasks:

I. Identification of cases and conditions. A variety of conditions are desirable for testing the AIRS forward model. For example, a very warm, wet case will provide a severe test of the water vapor channels and both warm and cold scenes are required for radiance validation. This exercise will also facilitate planning of future campaigns. The datasets that can be used for validation case selection include:
   - A. Existing data sets: CAMEX-I, CAMEX-II, OTIS, SUCCESS, WINCE, ARM SGP Cloud and Radiation Testbed (CART) site, etc..
   - B. Future preflight and postflight campaigns: CAMEX3
   - C. Continuously operating ground based sites: ARM CART sites, particularly during IOPs.

II. Compilation of upwelling radiance observations from HIS/NAST/Scanning HIS/AES. The number of data records that will be averaged on a flight line need to be carefully selected (e.g. to ensure clear sky conditions).

III. Compilation of ground-based radiance observations from the AERI at the ARM CART sites in Oklahoma, Alaskan North Slope, and the Tropical Western Pacific, and also the land and sea surface viewing AERIs. The temporal profiling capability of the AERI will expedite identification of observational data recorded during periods when the atmosphere was stable and homogeneous. This is an issue due to rise time and directional drift of radiosondes.

IV. Compilation of co-located temperature profile observations from sonde and other profile observations. Comparison of various sources provides an uncertainty estimate for the profile.

V. Compilation of co-located water vapor profile observations from sonde and other profile observations, such as Raman LIDAR (e.g. GSFC, ARM CART facilities). Microwave radiometers will provide accurate column integrated water vapor (e.g. ARM CART site). These data will be combined with other available in situ observations such as tower/tether sonde frost point hygrometers and chilled mirrors.

VI. Compilation of surface observations of temperature and emissivity from land- and marine-AERIs.

VII. Evaluation of selected cases. This would involve:
   - A. continued development of data visualization and analysis tools,
   - B. determination of clear/cloudy periods using Raman LIDAR, MAS, MODIS, GOES, etc.
   - C. determination of homogeneous periods
   - D. derivation of mean radiances and uncertainties,
   - E. derivation of mean temperature and water vapor profiles and uncertainties, and
   - F. derivation of land/sea surface temperature and emissivity, and uncertainties.

VIII. Provide cases in accessible form. This could be done by:
   A. conversion of radiance and atmospheric state data to NetCDF and/or ASCII format
   B. provision of a browse capability
   C. organization within HTML documents.
IX. Coordination of data exchange with related programs (DOE, ARM, NSF, etc.).

3.6 Statistical comparison of existing data sets

Pre-launch, we plan on developing the software and obtaining the relevant data sets needed to characterize the error statistics of existing data sets in terms of spatial and temporal modes. We will initially focus on atmospheric temperature and moisture as well as surface parameters such as temperature. The results of these studies will be critical to understanding the comparisons with these products to AIRS/AMSU-A/HSB products after launch.

3.7 Pre-flight Instrument Performance Validation

3.7.1 AIRS

The recent ATBD review for the PM1 instruments held in February 1997 and the PM1 maneuvers meeting held in May 1997 pointed to the need for the AIRS JPL team to conduct an instrument performance verification to validate the engineering performance data provided by Lockheed-Martin infrared Imaging Systems (LMIRIS) in Lexington, MA. The experience of the MODIS team in this area strongly backs the proposal made here by AIRS to undertake a similar "Instrument Performance Validation". So far the AIRS Team has relied solely on inputs from the engineering team at LMIRIS.

AIRS is currently in an ideal position to undertake this effort: As a result of the recent realignment of the Project, AIRS has been directed by GSFC to include an additional unit; an Engineering Unit (EM) to the instrument contract effort to be tested in the AIRS Test and Calibration Facility (ATCF) at Lockheed Martin (LMIRIS). This will reduce risk on the FM unit build, calibration, operation and the overall project as we now have an EM unit to test, calibrate and validate the following areas:

Software

Using the EM unit, the instrument spectral performance can be validated by the AIRS Science Team using the ATCF located at Lockheed-Martin Lexington Mass. To validate the performance the calibration software performance must first be validated to insure both radiometric and spectral accuracy are repeatable and consistent with accepted standards. Validation of the software using the EM unit first will insure a smooth transfer of this calibration to the FM unit acceptance test and calibration process. This validation of the calibration process will cover the bandpass of AIRS and include the hardware/software used in Fourier Transform Spectrometer (FTS) and Ground Support System (GSS). Validation will include absolute radiometric and spectral wavelength measurements using the ATCF secondary standard laboratory sources.

Testing (Retrofitted-EM and cross calibration to FM)

Validation of the calibrated EM unit performance will be transferred to the calibration of the FM unit to insure the spectral and radiometric performance and stability is properly understood and modeled. All the same software, laboratory sources, standards references and procedures used for the EM calibration/validation will be used and transferred to the FM unit.

Cross calibration of sources/instruments

The sources (radiometric and spectral) used in the AIRS ATCF will have their calibration validated through NIST using primary and secondary standards. This validation will be accomplished on a periodic basis by JPL and AIRS Science Team personnel to insure accuracy and traceability are maintained. The effort will include the radiometric blackbody sources and laboratory instrumentation. After calibration of the laboratory sources, filters and instruments this calibration will then be extended to the EM unit and then to the FM unit insuring a traceable, stable results. At this point cross calibration to other EOS instruments such as MODIS and CERES can be radiometrically and spectrally cross calibrated with AIRS to insure consistent results across the EOS data set.

Spectral (ATCF and EM)

Spectral calibration of wavelength and validation of the stability and repeatability of the calibrations will be accomplished by use of the FFT system, absorption lines in the residual chamber gas, LASER sources, filters and other sources. It is very important that the spectral calibration and stability be clearly characterized and understood in the ATCF, AIRS EM and FM in both preflight, flight and postflight. Sounding accuracy depends on a well founded calibration/validation process to completely understand the instrument spectral performance.

Radiometric (ATCF and EM)

Radiometric calibration and validation of these results starts with calibration of the blackbody sources via the NIST circuit using primary and secondary standards. These calibrations will be made over the temperature ranges expected in AIRS (195-350 K) during on orbit operation. Validation of these results end-to-end starting with calibrated sources and ending with detected energy at AIRS detectors must be understood for stability and longhaired over the dynamic range of AIRS. This stability and repeatability test-to-test, day-to-day over the long term must be understood to get a basis for the AIRS calibration related to sounding accuracy and other EOS instrument calibrations on the ground and in flight.

Operations

It is very important that instrument performance be validated for changes in the spacecraft environment (orbital maneuvering, thermal control drifts, power regulation etc.). This will allow the AIRS Science Team to adjust the calibration models if necessary and stay on top of the AIRS temperature sounding data and how it affects the temperature retrieval process. Comparisons between calibrations made in the ATCF and actual on orbit conditions can be simulated and tested on the ground using the EM unit in the ATCF throughout the mission. This process will be extremely valuable to transfer these calibrations to the NOAA, IPO and future instrument programs such as IMAS for data continuity.

After delivery of the Flight Unit in Oct. 98 to TRW we will have the EM Unit at LMIRIS to continue testing, calibration, and validation through spacecraft integration and test. As we operate the AIRS instrument in orbit we will be able to simulate and validate most conditions and results in the laboratory environment (ATCF) to understand the true radiometric and spectral performance of AIRS. Also, instrument response anomalies on orbit will be simulated by duplication in the ATCF so that informed, proper corrective action can be taken by the operations team.

Table 3.1. Key Instrument Calibration and Performance Validation

	PARAMETER	VALUE [units]	MEASUREMENT APPROACH	CALIBRATION	SCIENCE VALIDATION
1	Scene Dynamic Range	195K - 357K	Sweep LABB over dynamic range	Demonstrated FRD compliance	
	Radiometric Calibration Accuracy	Max(3%, 50/SNR)	Same test as above	FRD compliance proven by analysis	Curve fit for non-linearity correction
2	Scan Response Uniformity	<±2%	LABB at 300K and 250K all angles from ±50 degrees	Demonstrated FRD compliance	need two temperatures at all angles from ±50 degrees to validate polarization correction algorithm Validate that NeN is not scan angle dependent
3	Sensitivity (NEΔ T)	3.74- 4.17µm 0.2K 4.17- 4.21µm 0.14K 4.21- 13.4µm 0.2K 13.4-15.4µm 0.35K	LABB at 220K, 250K, 300K and 340K	Characterize rms noise at full dynamic range. Characterize 1/f noise (if any)	Indirect validation during the 24 hour test.
4	Spectral Coverage	3.74-4.61 µm, 6.20-8.22 µm, 8.80 -15.4 µm	FT-Interferometer	Acceptance test to demonstrated FRD compliance	
	FWHM @ 14mm Width at 50% of area Width at 95% of area Area outside λ± 6 Δλ	Δλ=λ/R R=1200 ± 5% 900< R < 1400 elsewhere < Δλ < 2 Δλ < 1/3000 of peak	Same test as above	Characterizes SRF at all wavelength with more than 1/3000 of peak response	Evaluate retrieval error if not FRD compliant Validate grating model for spectral calibration Validate non-linearity correction based on ghost suppression
	SRF centroid knowledge	0.01 Δλ	same test as above		
5	Wavelength Calibration stability in 24 hours	0.05 Δλ	24 hours test with gas-cell at nadir position		validate spectral calibration algorithm. validate frequency tracking algorithm
6	Spatial Response IFOV FWHM 99% of power 99.95% of power	 1.1 degree diam. <2.5 degree diam. <7.5 degree diam.	<0.5 degree point source scanned in azimuth and elevation		
7	Measurement Simultaneity	> 0.99	0.5 degree pointsource rasterscan in 1.5 degree diameter field	Calculate Cij from spatial response test	
8	Instrumental Polarization	<0.25% at λ < 5µm no spec at λ > 5µm	Rotate infrared polarizer between a black-body source	Measure polarization angle and principal axis at all wavelengths	validate polarization correction equation
9	spectral centroid and resolution absolute calibration		variable pressure gas cell		compare with calculated gas absorption depth and positions
10	end-to-end pre-paunch system test		Vertical look through earth atmosphere at night and day		compare with uplooking AERI interferometer compare with lfast-code

There are only ten generically different test needed to characterize and validate the radiometric and spectral performance of the AIRS instrument. Some of these tests have to be run in several test conditions, such as different LABB source temperatures. Due to aperture illumination and SNR limitations, test 4 using the FT interferometer has to be run in at least eight different configurations. Note: LABB is the Large Area Blackbody in the ATCF chamber. It covers the full aperture. The AIRS Calibration Plan gives additional details on the tests and test equipment.

Science Analysis and Instrument performance validation tasks:

1. The sweep of the LABB from 195K to 357K verifies the instrument dynamic range. Derive the non-linearity correction equation from these data. Validation of the non-linearity correction equation uses test 4.
2. Observation of a target at fixed temperature at various scan angles, while using the internal calibration, should result in measurements of the target temperature within the absolute calibration permitted by the FRD. The scan angle dependent polarization correction equation is adjusted until this is true. Validate the correction equation by using a second LABB temperature.
3. Indirect validation of the NEN and 1/f noise characteristics is possible using the 24 hour test data.
4. A grating geometric model is needed for the spectral calibration.
   a) Derived the grating model from the knowledge of the spectral centroid of each detector.
   b) Independently assess the SRF FWHM for each channel.
   c) A interferogram taken with inadequate non-linearity correction exhibits spectral ghosts in predicable locations. Use this to validate the non-linearity correction algorithm, using the coefficients derived from test 1.
   d) After suppressing any false ghosts, analyze the SRF for real ghosts and spectral leaks.
5. In the 24 hour test the instrument is in the normal data taking mode, with the scan mirror rotating and producing calibration and cold space views every 2.67 seconds. The external environment of the instrument is adjusted using heaters to simulate orbital conditions. The nadir view looks through the spatial collimator at a 300K blackbody. The spatial collimator is filled with a low pressure gas (TBD type and pressure).
   a) Validate the ability of the spectral calibration algorithm to determine the centroid of each detector.
   b) Validate the performance of the spectral tracking algorithm.
   c) Validate the stability of the radiometric calibration
6. Validate Out-of-field rejection with regards to the contamination of the space view from the Earth horizon.
7. Use two-dimensional Gaussian bell curve fit to the spatial response scans to evaluate the Cij. The contractor calculates Cij by comparing the difference between the centroids of the spatial response functions of different detectors. Validate the contractor's result for all wavelengths.
8. Determine the instrumental polarization and orientation of the major axis of the polarization ellipse for all wavelengths. Validate the result using test 2.

9. In the gas cell test the instrument is in the normal data taking mode, with the scan mirror rotating and producing calibration and cold space views every 2.67 seconds. The nadir view looks through the spatial collimator at a 300K blackbody. The spatial collimator is filled with a low pressure gas (TBD type and pressure). The gas pressure is changed in six predetermined steps every 10 minutes. Compare the observed spectrum (transmission feature centroid and depth) to calculated spectra. This is an end-to-end test of the radiometric calibration, spectral resolution and spectral calibration.
10. Make measurements of the downwelling spectral radiance (look at zenith) from clear sky at night and day for 10 minutes each, by looking through the special external window of the ATCF. Compare with calculated spectra and simultaneous spectral radiance measurements using the AERI.

Instrument Calibration Tasks: To be described in the AIRS Calibration Plan and AIRS Calibration Implementation Plan (November 1997)

3.7.2 AMSU-A and HSB

The following discussion pertains to all three microwave instruments — AMSU-A1, AMSU-A2, and HSB — unless noted otherwise, since these instrument are in many ways quite similar. Pre-flight activities will follow two distinct tracks.

Analysis of Instrument Test Data

The first track is similar to, but much less extensive than, that of AIRS. It involves analysis of test data from each instrument . All three FM units (there are no EM units) will be subjected to extensive thermal-vacuum radiometric test suites as well as other tests (such as antenna pattern measurements). These tests will be used to verify compliance with performance requirements and to determine calibration parameters, as well as to predict operational characteristics. Thus, the test data will be transferred to the TLSCF for analysis and archived for use as a baseline reference on instrument performance. The data will also be used to exercise parts of the processing software, such as the L0-to-L1a software and portions of the calibration software.

In summary, this track will consist of the following activities:

a. Analysis of test data —> Performance verification —> TLSCF archive
b. Analysis of test data —> Calibration parameters —> S/W tables
c. Analysis of test data —> Baseline performance signatures —> TLSCF archive
d. Test data —> Processing S/W segments (input) —> S/W modifications

Activities Associated With NOAA-K

The second track consists of analyzing AMSU-A and AMSU-B data from NOAA-K, which is scheduled for launch in 1998. These instruments are nearly identical to the corresponding EOS instruments. Therefore, although the NOAA-K orbit is quite different from the EOS-PM1 orbit (7:30 AM vs. 1:30 PM ascending node, 823 km vs. 705 km altitude) and the NOAA platform environment differs from the EOS-PM1 environment, it will be possible to use performance analysis of the NOAA instrument data to predict performance of the EOS instruments. The same data will also be used to exercise the entire microwave L0-to-L2 software.

It is our intention to participate in the post-launch efforts to validate the NOAA-K microwave instrument performance and associated data products. This presents a unique opportunity to prepare for similar activities following the EOS-PM launch by letting us exercise the AIRS microwave data processing system as well as segments of the AIRS validation system.

This track will consist of the following activities:

a. Repackage NOAA telemetry to EOS format
b. Process reformatted telemetry through AIRS L0-L2 S/W (microwave only)
c. Validate AIRS L0-L1b S/W: compare calibration coefficients with NOAA's
c. Validate instrument performance: analyze L0 and L1a/b data
d. Validate calibration processing: analyze L1b products
e. Validate retrieval processing: analyze geophysical parameters

The instrument performance analysis will include statistical analysis to estimate system noise and other parameters, comparison with pre-launch test data and identification of trends and patterns in the raw and calibrated instrument data.

The calibration analysis will include similar analysis of the derived calibration coefficients, determination of the correlation between the Earth brightness field and the cold calibration brightness. We plan to take advantage of any opportunity for vicarious brightness temperature validation as well.

Finally, we plan to use in situ measurements as well as geophysical products from other (validated) satellite sensors to validate the various microwave derived intermediate geophysical products (e.g., temperature, water vapor and liquid water profiles, surface type, and rain flag). The procedure will be the similar to that described in section 4 (Post-Launch Activities), with the exception that we will use mostly in situ data made available through NOAA's validation efforts.

It is our intention to establish close collaboration with NOAA for this effort. We expect both parties to benefit from AIRS participation.

3.7.3 VIS

Pre-flight validation activities of the visible/near-IR detectors can be divided into two parts: instrument performance validation, and testing of the in-flight validation process.

Instrument Performance

The AIRS Engineering Model will not include the visible/near-IR channels, so the instrument validation can only be performed on the Flight Model. All items specified in the AIRS Functional Requirements Document (FRD) will be verified, but it is particularly important to characterize the following five parameters as well as possible.

Instrument Spectral Response. Specifications are given in Section 3.1.4.2 of the FRD, and Fig. 2.5 shows predicted response functions. The output of each visible detector sub-element will be measured under monochromatic illumination. (Sub-element refers to one of the ten detector elements that are combined to form a pixel, see Fig. 2.4.) By stepping the illumination through the relevant wavelengths, spectral response will be measured. Each detector element will be tested while all other elements are masked. (Readouts from masked detectors will be recorded to test detector cross-talk, see below.)

Instrument Spatial Response. Section 3.1.3 of the FRD specifies a 0.185 (± 5%) degree full-width-at-half-maximum for each VIS pixel. This will be tested by measuring both pixel and sub-element output as a collimated light source is moved through all viewing angles.

Instrument Sensitivity. Section 3.1.5.3 of the FRD specifies a signal-to-noise ratio of at least 100:1 when viewing an extended sunlit surface with a uniform albedo of 0.4. This will be confirmed by imaging of an artificial surface of the specified albedo under simulated solar illumination. The noise level will be determined by repeated imaging of the same surface, and by dark-current measurements. (The Detector Linearity test, described below, will also collect data relevant to sensitivity.)

Polarization Response. The FRD specifies that the response to photons of any two, orthogonal polarizations of equal intensity shall differ by no more than 5%. This will be tested by viewing an unpolarized light source through a linear polarizer, the polarizer being stepped through a 180° rotation.

Co-alignment. The boresight of each VIS array shall be within 0.185 degrees of the IR boresight (Paragraph 3.1.3 of the FRD). In addition, the across-track separation of any two VIS channels shall be less than 0.0185 degrees, and the long axis of each detector array shall be within 0.001 radians of the instrument x-axis. These items will be measured using a collimated light source, and by imaging of test patterns.

There are five additional pre-flight characterizations planned, which are not specifically contained in the FRD:

Detector Cross-Talk: This will be measured between all pixels and between all pixel sub-elements. The testing procedure is to measure the dark-current of all detectors, to measure the response in all detectors when one is illuminated and the others are masked, and to measure the currents when all detectors are illuminated. Imaging of a checkerboard pattern with the full detector array may also be useful.

Scan Mirror Homogeneity at Visible/Near-IR Wavelengths: Measurements of the mirror reflectivity, polarizability, and emissivity, as a function of position on the mirror, must be obtained in the wavelength range 0.35 to 1.1 microns. The mirror should be characterized on a scale approximately 10% of the size of the projection of a visible pixel on the mirror.

Detector Linearity. The response of each sub-element to radiances between zero and saturation will be determined. This can be achieved by masking all sub-elements except the one to be tested, and then imaging a diffuser plate as the illumination is increased from zero until detector saturation. (This also serves to measure the dynamic range of the detectors and noise level.) If cross-talk is negligible, all detectors can be tested simultaneously.

Ghost Images: The extent to which a sub-element or pixel holds a detectable after-image should be determined. This can be done by first measuring each sub-element's dark current. Then, the sub-element is exposed to a bright field-of-view (comparable to a sunlit cloud), for a time corresponding to several read-outs. (Operationally, each sub-element is expected to be read every 3.828 milliseconds, with a 2.801 millisecond integration time.) Just before start of the next integration, the illumination is shut off, and the next read-out is compared to the original dark current measurement.

All Other Parameters Relevant to the Instrument Model: As described in Jovanovic′ and Hofstadter (1997), a detailed instrument model is needed for geolocation and in-flight calibration of VIS. Each of the parameters in the following table, along with an uncertainty measure, must be determined.

Parameter	Nominal Value
Effective Focal Length	77.427 mm
Number of pixels across-track in one scan	540
Number of pixels along-track in one scan	9
Coefficients to account for non-linearity of scan rate (Coefficients for a third order polynomial are shown as the default, with the scanning linear in time.)	[0, 1, 0, 0]
Scan mirror tilt	45°
Total across-track angular coverage	99.0°
Total along-track angular coverage	1.665°
Misalignment between instrument coordinate system and spacecraft coordinate system [roll, pitch, yaw].	[0°, 0°, 0°]
Scan mirror rotation period	2.667 seconds
Interval between reading consecutive pixels in an array	6.0E-5 seconds
Interval between consecutive readouts of the same pixel	3.828E-3 seconds
Time offset between channels	0 seconds

Validation Process Testing

In addition to the instrument characterization, part of the pre-flight validation is to test and improve the procedures and algorithms for in-flight validation. This process consists of passing simulated AIRS data through the entire in-flight validation process. There are two sources of simulated data. The first is the AIRS forward model, as described elsewhere in this document. In addition to the visible, IR, and microwave radiances, supporting data are the Level 2 "Truth Files" used to generate the data, and, for truth files based on NCEP's Medium Range Forecast Model, the radiosonde, station reports, and satellite data used as inputs to the MRF model.

Another source of simulated visible data is to use other instruments flying before the launch of AIRS. The AVHRR instrument, aboard NOAA's polar orbiters, has spatial resolution comparable to VIS, and AVHRR channels 1 and 2 have a spectral response similar to VIS channels 2 and 3, respectively. Supporting data in this case are radiosonde and weather station reports, TOVS data, and any field campaigns with a satellite over-flight.

The MODIS instrument, to be flown on both the AM-1 and PM-1 EOS platforms can also be used to simulate AIRS VIS data. As described in sections 4.3.3 and in Aumann *et al.* (1996), a linear combination of MODIS channels can be used to approximate the spectral response of each VIS channel. Supporting data are provided by instruments orbiting with MODIS (such as CERES and AMSR), ground campaigns, and standard radiosonde and weather station reports.

4 Post-launch Activities

4.1 Field Campaign Studies

After the launch of AIRS, regular observing campaigns/IOPS should be conducted to continue spectroscopic and forward model validation, and provide for validation of the AIRS fast forward model. Instrumentation for such campaigns should be similar to that previously discussed for the pre-launch spectroscopic and forward model validation campaigns. The major instrumentation addition, of course, will be AIRS/AMSU-A/HSB onboard the EOS-PM platform. This adds the logistical complexity of coordinating surface, in situ, and aircraft observations with the overflight track of AIRS. However, cross-track scanning broadens AIRS geographic coverage. Due to AIRS global coverage, global coverage of validation campaigns is desired. Thus, the different campaigns/IOPS should occur at different sites, possibly using the DOE ARM sites or other EOS validation sites as bases of operation. One of the primary objectives here is to examine H_2O spectroscopy under very different conditions of total atmospheric H_2O amount: large in the tropics and small in polar regions. However, as previously mentioned, open ocean sites are the most desired locations to simultaneously validate both upper and lower tropospheric H_2O.

Although remote observations will be obtained by AIRS/AMSU-A/HSB, we will still desire ER-2 flights with a full suite of remote sensing instruments including IR interferometer/spectrometer, IR/Visible imager, and microwave as well as LASE. It is particularly important to validate AIRS upper troposphere H_2O with a well designed campaign since radiosonde water vapor measurements have large systematic errors at pressure below 300-400 mbar. This can be accomplished by flying LASE (H_2O LIDAR) with the IR interferometer/ spectrometer to obtain coincident observations of upper tropospheric H_2O.

Aircraft Underflights

Instruments to be flown on aircraft, in particular the NPOESS Atmospheric Sounder Testbed (NAST) being developed for the NASA ER-2, will play a most important role in the validation of AIRS observed radiance spectra and AIRS/AMSU-A/HSB retrieved products. As mentioned in Section 3.3, the NAST consists of a Michelson Interferometer, called NASTI, and microwave radiometers with the AMSU-A/HSB spectral channels, called NASTM. The NASTI spectral resolution of 0.2 cm^{-1} is sufficiently high that AIRS spectral radiances can be accurately simulated through a transform utilizing the AIRS and NASTI instrument response functions. The spatially scanning two kilometer NASTI footprints can also be spatially convolved with the AIRS spatial response functions to alleviate any geographical sampling differences between the two instruments. Remaining discrepancies of radiance expected from the inexact transformation of the NASTI spectral response to that of the AIRS will be alleviated using corrections based on theoretical calculations of these residuals based on profile observations (e.g., the AIRS retrieval or in-situ profile measurements).

Other aircraft radiometers which will play an important role in the validation of AIRS observed radiance spectra are the nadir viewing ER-2 HIS, which will provide an independent check of the NASTI measurement accuracy, and the MODIS Atmosphere Simulator (MAS) which will provide detailed spatial measurements of radiance at lower spectral resolution than AIRS. In the case of MAS validation, the AIRS spectral radiances will be convolved using the MAS spectral response functions, while the MAS observations will be spatially convolved using the AIRS spatial response function. The MAS will play an important role in alleviating validation uncertainties due to the spatial variability of radiances within the AIRS footprint.

Product retrievals from ER-2, NAST, HIS, and MAS data also will be used to validate AIRS product retrievals. Here the much higher spatial resolution of the aircraft data plays an important role of validating AIRS products under the conditions of variable surface and atmospheric radiance (e.g., due to clouds) within the AIRS footprint. For these retrieval comparisons, the same retrieval physics used for AIRS (i.e., that of the team algorithm and that of the RAVM) will be applied to the aircraft measurements in order to unravel the source of discrepancy between the two products (i.e., AIRS and ER-2). Whenever possible, these comparisons will be performed where independent in-situ and ground based remote sensing data are available (e.g., the DOE ARM CART sites) in order to provide completely independent validation of the ER-2 products used to validate the AIRS/AMSU-A/HSB retrievals.

Surface Product Validation

Validation of sea surface temperature, land surface temperature, and land surface emissivity science products can be performed with a unique complement of instrumentation that has recently been developed at the University of Wisconsin-Madison. Accurate measurement of the infrared skin temperature and emissivity from a ground- or ship-based observing platform is possible. The instrumentation is an enhancement of the zenith viewing AERI system that allows for angle scanning in a plane over a 180 degree range of angles from nadir to zenith.

The marine version of the scanning AERI instrument, known as the Marine-AERI (or MAERI), can be mounted on the side of a ship to obtain accurate observations of the upwelling radiance spectrum from the ocean surface at several angles as well as a complement of angles of the downwelling radiance from the atmosphere. Unique processing techniques developed at UW-Madison (Smith *et al.* 1996) have been used to process data from two ocean going cruises to obtain state-of-the-art measurements of the ocean skin temperature and the ocean infrared emissivity spectrum as a function of incident angle. The success of this instrument has already led to the fabrication of three operational MAERI instruments for use by the MODIS science team in the validation of the MODIS sea surface temperature product. The AIRS validation plan should make use of similar instrumentation for the validation of the AIRS sea surface temperature core product. Due to the higher spectral resolution of the AIRS instrument, the accuracy of the AIRS surface temperature product (over the AIRS footprint) should be higher than that of MODIS and could be used as a comparative reference for MODIS assuming that the AIRS sea surface temperature product has itself been validated. The AIRS validation plan includes collaboration on sea surface temperature product validation with the University of Miami and the MODIS team.

The land version of the scanning AERI instrument is currently in a prototype configuration installed in a mobile research vehicle. It is mounted on a telescoping hydraulic ram that allows the instrument to be raised about 16 feet above the ground for land surface viewing. This mobile instrument configuration has proven useful in obtaining grass and bare soil skin temperature and spectral emissivity measurements at the DOE-ARM Southern Great Plains site in September 1996 and snow surface temperature and emissivity measurements during the January 1997 WINCE experiment in Madison. These observations have demonstrated the capabilities of this measurement technique and have been used to develop the tools to analyze this type of data. This mobile research vehicle can be used during campaigns in the continental United States for validation of AIRS surface temperature and emissivity products. These measurements should be coordinated with those planned for the MODIS instrument by working with the MODIS science team members responsible for land surface validation.

The fabrication of a dedicated land-AERI for routine and continuing validation of AIRS temperature and emissivity products during the AIRS operational period should be considered. Since Australia is likely to become a key ground truth site for the EOS PM-1 platform due to the temporal sampling characteristics of the platform orbit, consideration should be given to installation of a land-AERI at a ground site in central Australia. The installation and maintenance of this instrument would be handled in close collaboration with Dr. Mervyn Lynch of Curtin University, Perth, W. Australia who is intimately familiar with the AERI instrument and is already a part of the MODIS surface product validation activities.

Consideration should also be given to establishing a land validation site on the Antarctic Plateau (e.g. Dome C, a French station at 74.5S, or Plateau station at 79S) in collaboration with NSF-funded investigators (Drs. Von Walden, U. Wisconsin and Steve Warren, U. Washington). These locations have cold, stable surface temperatures throughout the year with an infrared emissivity of near unity. The surface temperatures of the Antarctic Plateau are similar to those found at tops of clouds in the upper troposphere at lower latitudes. The Antarctic atmosphere has no confusing water vapor continuum emission in the longwave infrared window (800-1200 cm^{-1}) because of the low column water vapor amounts (1 mm of precipitable water in summer and 0.3 mm in winter). In the clearest portions of the window, satellite instruments actually view the Antarctic surface with little emission from intervening gases. A downward viewing AERI can then provide accurate validation data on the surface emissivity and skin temperature without the need for expensive aircraft overflights. A lidar would be necessary to ensure that sub-visible cirrus and polar stratospheric clouds are not in the satellite field-of-view. Since a downward viewing AERI can accurately determine the surface skin temperature and its variability, this would allow radiometric validation of AIRS radiances over a cold target. This would avoid problems associated with using emission from cloud tops with ill-defined temperatures.

Land Surface

The land surface is inherently non-uniform on the scale of the AIRS footprint and characterizing a land target on these scales may well be one of the major obstacles to a land-based correlative measurement program. We note that in the draft MODIS Land Integrated Validation Program (Justice, 1996) it is recommended that extent of the land validation sites be the order of (185x185 km) and that "... the intent is to use these sites for multiple instrument validation and to provide a focused location for high spatial and temporal resolution (land surface) data acquisition". The intention to have the MODIS Test Site Concept developed into an EOS Test Site Program would be beneficial to the AIRS validation program and, as such, is endorsed by the AIRS Team.

Presently, the concept is for such sites to include a small number of large towers equipped with radiation, flux and ground measurements; a larger set (order of 10 or 12) of instrumented permanent sites, inclusive of smaller towers; and an extensive array of 40 to 60 sites equipped with land surface and atmospheric sensors. This concept, which has advanced to the EOS Validation Office, should be monitored by the AIRS Team and supported when the opportunity arises. If the proposal does proceed, it should be in place for the EOS AM- 1 platform validation in 1998, and certainly in a mature state of operation with good surface characterization by the launch of AIRS in 2000.

The DOE ARM/CART site in Oklahoma is a further prospect for validation because of the very specialized instrumentation which is in place at the central facility. The addition of the four perimeter facilities extends the site so that it may be used to support validation of the larger footprint sensors such as AIRS. While these sites are not yet fully operative, a network of solar photometers are already in place and ground-based AERIs are approaching delivery and installation at the perimeter sites. This DOE site offers a different set of supporting validation data to the proposed MODIS Test Site Program in that it will be more focused on defining the atmospheric uniformity above the land target. Data from this (and possibly other DOE ARM sites) will permit improved atmospheric modeling; a particularly important component of the validation of land surface products.

It is easier to find homogeneous surfaces on the scale of the visible/near-IR (~2 km). White Sands, New Mexico is such a place, and is to be used for validating, even calibrating the visible detectors. As discussed in Aumann et al., 1996, other desert and even semi-arid regions can be used, though the presence of vegetation can complicate the analysis.

A final component of the validation program which needs investigation is the capability for using the Baseline Surface Radiation Network (BSRN) sites to support land product validation. BSRN is part the Global Energy and Water Cycle Experiment (GEWEX). The BSRN program includes a network across many continents and a variety of land cover types. Typically, these sites measure both the incoming solar spectral irradiance, the surface bi-directional reflectance and the broadband albedo from the visible through to the near IR. Further, the thermal IR fluxes (up and down) are also determined along with surface emissivity. While these sites may vary in comprehensiveness regarding their complement of instruments, they do offer the advantage of an established baseline network that will have achieved considerable experience in characterizing the diverse range of properties represented by these sites, specifically their spatial homogeneity and their seasonal variability.

With respect to ATBDs in related programs, we cite the very comprehensive MODIS Land-Surface Temperature ATBD - Version 3 (Wan, 1996) which collects together the relevant literature and recommends a specific form of the MODIS land surface temperature algorithm. While the AIRS algorithm will differ from the MODIS version, there will be benefit in a comparison of the common products derived by AIRS and MODIS, such as the land skin temperature and the associated emissivity. The issues of spatial and spectral resolution, of course, must be treated appropriately as mentioned elsewhere in this document. Of importance will be the comparison of common land products, the associated algorithm validation for both day and night conditions, and also for the range of sites embraced by the surface network.

Ocean

To derive surface parameters from AIRS on-orbit, radiometric measurements require an accurate specification of the thermodynamic state (temperature and moisture profiles) of the intervening atmosphere, information on the sea state and surface wind (because of their effect on surface emissivity) as well as the specific geometry at which the ocean is viewed by the sensor. These requirements may be translated into a specification of a minimum configuration of measurement instruments and accuracies for the validation of ocean surface products. The requirement is for multi-sensor validation measurements at a number of global locations which span the polar regions, the mid-latitudes, and the tropics. The validation also must test the performance over a range of seasonal conditions experienced at those sites.

A strategy to address these requirements embraces both intensive field campaigns together with a sustained level of ongoing measurements designed to detect changes in instrument performance due to, for example, instrument drift or optics/sensor degradation.

Ocean surface validation programs typically are more problematic to implement and support over time when compared to land surface validation sites. As a consequence, ocean surface validation sites and associated programs are typically compromised. Validation programs used for some of the current generation satellite sensors for determining ocean skin temperature, for example, have been of moderate accuracy (ΔSST $\approx \pm 1$ K) and comparable accuracy validation has been possible, frequently using operational measurements from ships of opportunity and the global radiosonde network. If the radiometry and derived products from next-generation sensors, such as MODIS, ASTER, and AIRS, are to be validated to an accuracy which is sufficient to establish the performance of the sensors and the accuracy of the products, then an improvement in current validation practices is essential.

How to meet the improved accuracy, both in the intensive field campaigns and in the longer term measurements associated with ongoing field validation programs, is a key issue for resolution by the AIRS science team. We outline the requirements below.

Intensive Ocean Field Programs

Oceanographic research vessels equipped with a complement of radiometric and *in-situ* sensors, such as used in TOGA-COARE, GULFMEX, and CSP generally are able to provide high accuracy surface measurements suitable for use in validation.

Validation of the upwelling ocean surface radiance may be achieved using ship-deployed calibrated spectroradiometers such as the Marine-Atmospheric Emitted Radiance Interferometer (M-AERI) (Smith *et al.*, 1996) or broadband infrared thermometers. The M-AERI is a variant of the High-resolution Interferometer Sounder (HIS) which normally is flown on high altitude aircraft to determine the TOA spectral radiance (Smith *et al.*, 1995). The M-AERI has a number of attractive attributes because it measures several key quantities; namely, the downwelling atmospheric spectral radiance as well as the upwelling ocean radiance (at several zenith angles) which includes the ocean emitted radiance and the reflected sky radiance. The use of internal blackbodies for radiometric calibration and a laser for maintaining spectral accuracy (from 3.3 to 18 μm) provide the capability to derive ocean skin temperature and emissivity as well as retrieved atmospheric temperature and humidity profiles (Smith *et al.*, 1996). Present plans are for M-AERI instruments to be used in the intensive field campaigns and also for one (possibly two) to be installed on a fixed ocean research platform for the conduct of long term measurements over a range of atmospheric and ocean conditions (see section below). Also, an Unmanned Airborne Vehicle (UAV) interferometer is under construction for DOE and this also may be used to provide ocean spectral radiances from aircraft.

Broadband IR thermometers may be mounted on ships (Schlussel *et al.* 1987) and also on low flying aircraft platforms (Rudman *et al.*, 1994) to achieve increased spatial sampling simultaneously with satellite overpass time. These instruments have the advantage of high accuracy, low cost and high temporal sampling.

The more conventional *in situ* thermometers, operating either as free drifters , attached to moored buoys (Strong and McClain, 1984) and deployed from ships (Llewellyn-Jones *et al.*, 1984) typically make high accuracy measurements at a relatively high sampling frequency. Some of the latter are relatively inexpensive and offer the only real opportunity to provide global coverage at a manageable cost. It would be however desirable for AIRS validation to achieve some compatibility of sensors in the global program, with a serious attempt being made to intercalibrate the sensors in one laboratory. We cite here the example of the AERONET program (Holben, *et al*.., 1996) that progressively is achieving global coverage with a network of identical sunphotometers that are calibrated routinely at one location.

Spurious events, such as volcanic eruptions, high loading of carbonaceous aerosol (from biomass burning) and transported continental dust, cause disruption to SST measurements programs because of the scattering /absorbing/emissive properties of the aerosol in the LWIR. In this respect, data from the AERONET (Holben, *et al*., 1996) would support the screening of AIRS data and identify such problems. It might additionally offer the prospect of correcting the SST for the impact of the aerosol. While dust and biomass burning sources are of short term impact, the volcanic aerosol effect on SST may persist for several years and accordingly require frequent adjustment to the AIRS algorithm.

4.2 Spectroscopic & Forward Model Validation

Post-launch spectroscopic and forward model validation will focus on comparisons on comparisons with actual AIRS radiances. It is expected that many of the issues addressed in 3.1 and 3.2 will be refined, especially the spectroscopy of the upper tropospheric water vapor. We will emphasize the interplay between tuning and changes to the spectroscopy/forward model.

4.3 Long term intercomparisons

Part of the strategy for the validation of AIRS geophysical products is the participation in longer-term field campaigns. One of the most ambitious is GEWEX and is described below. GEWEX will act as a long-term validation umbrella for AIRS.

The Global Energy and Water Cycle Experiment (GEWEX) is a program initiated by the World Climate Research Program (WCRP) to observe, understand and model the hydrological cycle and energy fluxes in the atmosphere, at land surface and in the upper oceans. The goal of the GEWEX Program is to reproduce and predict, by means of suitable models, the variations of the global hydrological regime, its impact on atmospheric and surface dynamics, and variations in regional hydrological processes and water resources and their response to changes in the environment, such as the increase in greenhouse gases. GEWEX will provide an order of magnitude improvement in the ability to model global precipitation and evaporation as well as accurate assessment of the sensitivity of atmospheric radiation and clouds to climate change. GEWEX Projects include:

1. Hydrometeorology and Land-Surface Projects
    - GEWEX Continental-Scale International Project (GCIP)
    - Global Runoff Data Centre (GRDC)
    - International Satellite Land-Surface Climatology Project (ISLSCP)
    - Regional Continental-Scale Experiments (CSEs)
    - Baltic Sea Experiment (BALTEX)
    - GEWEX Asian Monsoon Experiment (GAME)
    - Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA)
    - Mackenzie River GEWEX Study (MAGS)

2. Radiation Projects
    - Baseline Surface Radiation Network (BSRN)
    - Cloud Profiling Radar Project
    - Global Precipitation Climatology Project (GPCP)
    - GEWEX Water Vapor Project (GVaP)
    - International Satellite Cloud Climatology Project (ISCCP)
    - Surface Radiation Budget Project (SRB)

3. Modeling and Prediction Projects
    - GEWEX Cloud System Study (GCSS)
    - GEWEX Numerical Experimentation Panel (G-NEP)
    - Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS)

<u>Long term monitoring of specific sites</u>

Data will be routinely collected from AIRS/AMSU-A/HSB for approximately 15 small regional sites scattered across the globe for long-term bias and trend comparisons. This data set will consist of the associated radiances and Level 2 products. The sites tentatively selected are:

- Warm Pool (Tropical), Central Pacific (Tropical), Indian Ocean (Tropical), Amazon (Tropical)
- Gulf of Mexico (Sub-Tropical)
- White Sands (Mid-latitude), Mississippi flood plains (Mid-latitude), Tundra (Mid-latitude)

- North Pacific Ocean (Mid-latitude), Southern Oceans (Mid-latitude)
- Polar Regions

Long-term Sea Surface Temperature Measurements

The longer term monitoring of the performance of AIRS in measuring SST is important to the maintenance of product quality over the period when issues such as sensor degradation and spurious atmosphere or ocean events might occur. Previously, we cited examples of volcanic aerosol etc. which might impact algorithm performance. These longer term programs typically will comprise in-situ measurements of SST, using a widely distributed network of in-situ sensors, because the requirement is to sample the full range of conditions from the tropics to the polar regions. Assessing differences between the in-situ and satellite SSTs due to algorithm or instrument performance will require other information, in particular atmospheric profile data from high grade radiosondes, for example. The task will be aided further if several validation sites are additionally able to make measurements of the upwelling and downwelling spectral radiances at the surface, using for example, the M-AERI. The ability to apply these data to modeling the sensor detected radiance with radiative transfer models will assist in determining the deficiencies in the AIRS algorithm. Outcomes of these activities will indicate if any possible changes are required to the algorithm.

Satellite Observations

Spectral radiance observations and retrieved products from other satellites will play an important role in the validation of global AIRS radiances and derived products, particularly for satellites which contain instruments with well known radiometric and derived product characteristics and possibly better than expected AIRS product retrieval performance (e.g., the upper atmosphere).

Operational

Radiance measurements and retrieved products from operational satellites will play a role in AIRS validation because of their well documented error characteristics. In particular, spectral radiances and profile retrieval products from the NOAA and DMSP series polar orbiting satellites and the geostationary GOES-east and GOES-west can be used with aircraft and surface-based ground-truth to experimentally validate the fact that AIRS/AMSU-A/HSB products achieve the improvements expected from theoretical considerations. This experimental demonstration of product improvement is key to the declaration of the successful achievement of the AIRS program. In order to validate an improvement in performance over current operational systems, a very carefully selected data set, representing different geographical and meteorological conditions, will be constructed. These cases will include, whenever possible, the same situations to be analyzed previously mentioned. The emphasis here is to be placed on having operational satellite products as well as ground or air-truth validation data.

Experimental

Certain experimental satellite systems will contain instruments which may be capable of better radiometer and retrieved product performance than that of AIRS/AMSU-A/HSB. The very high spectral resolution and limb scanning Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) and the GPS-MET satellite are examples of such a system. Other systems may emerge from NASA's NMP and ESSP small satellite programs designed to support the EOS system of measurements. Although not yet well defined, these experimental satellite measurements will certainly play a role in providing validation data in atmospheric regions where other types of in-situ, ground-based, or aircraft data are lacking (e.g., remote geographical regions and the middle and upper atmosphere).

4.3.1 Internal Consistency

The AIRS spectral radiances contain redundant information in terms of their dependence on surface and atmospheric parameters. This redundancy results in strong physical correlations of the radiances observed within one spectral region with those observed in another. For example, the tropospheric emission observed in the 15 μm CO_2 band should be highly correlated with that observed in the 4.3 μm CO_2 band. These relationships between spectral bands can be defined by regression analysis of theoretical calculations of radiance spectra using radiosonde observations.

After AIRS is on orbit, an internal consistency validation will be performed whereby the theoretically based regression relations between spectral bands will be applied to the observed AIRS spectra. The discrepancy between the regression prediction of one band of radiances from another band of radiances will be compared with the discrepancy expected from their differences in information content due to measurement and forward model uncertainties, as defined *a priori* by the regression analysis of the theoretical calculations. This validation of internal consistency differs from the external validation via direct comparisons of observed and calculated radiance in that the systematic error of measurement does not impact the result. It is also noted that internal consistency of the AIRS spectral radiances is a prerequisite to the achievement of the full vertical resolution potential of the AIRS system. This is similar to what is being done for pre-retrieval quality control.

Another form of internal validation consists of analyzing the discrepancies between the observed radiances and those calculated from the AIRS retrieval products using both a Fast Forward Model (used in the retrieval process) and the RTVM. Discrepancies between the calculations and observations which exceed those expected from instrumental noise and forward model errors will reveal any deficiencies in the AIRS spectral radiance measurements, forward radiative transfer model, and the retrieved products. The source of these deficiencies will be revealed through a comparison of the Fast Forward Model and the RTVM results, and through comparisons of these results with those arising from the other internal and external validations to be performed.

There are several qualitative consistency checks that can be made with VIS products as well. Regions for which the low-cloud flag is true, or the IR cloud fraction is high, should appear as bright in all four VIS channels. Features that trigger the surface inhomogeniety flag should be relatively faint in VIS 1, because that channel is most sensitive to scattering from atmospheric aerosols. Finally, a high correlation is expected between VIS 1 radiances and retrieved cloud fraction.

4.3.2 Radiosonde collection

Validation data for AIRS can come from two sources. One is a campaign designed specifically for validation. The second is to use data routinely collected for input to meteorological models. Both have their advantages and disadvantages. The advantage of routine data is that it is easier to obtain a statistically representative sample. Another consideration is that, if the data are to be used in numerical forecast models, consistency with other data can be as important as absolute accuracy. This is because it is, to a large extent, the gradients that determine weather. In any case, the rest of this section will discuss the types of routine data available for validation.

The best known is the radiosonde. They are widely flown and provide information about both temperature and humidity. They are used for both validation and tuning, and there are significant distinctions between the two. The difference stems from the fact that tuning is done on the radiances. Thus, the entire atmosphere is required to construct a radiance. Depending on the channel, this means that some of temperature, moisture, surface skin temperature, upper atmospheric temperature, and trace gas concentration must be known. For validation, only the parameter being evaluated is required.

For validation purposes, radiosondes have limitations. One is that the temperature sensor responds to both its local temperature environment and its radiation environment. Depending on its coating, the temperature at a level is influenced by temperatures at other levels and the incoming solar radiation. For some instruments, the infrared emissivity (and thus the above effect) is small. All instruments are affected by the solar radiation. Some measurements are corrected for these effects, but the corrections are not always an improvement. One instrument uses the vertical velocity to correct for a parameter that is determined by the velocity of the air past the sensor. While the average vertical velocity is indicative of the rise rate of the balloon, variations about this value during flight are caused by vertical motions of the air column. The velocity past the sensor is more directly related to the derivative of the vertical velocity, since the balloon adjusts very rapidly to changes due to its large area compared to its mass. For moisture, radiosondes are even more questionable. Radiosondes measure the value along a path as the instrument rises and drifts. Satellites measure water vapor over an area. Because of the large local variability of water vapor, these differences can lead to significant differences between the two measurements. In addition, water vapor is difficult to measure in the low concentrations and cold temperatures characteristic of the upper troposphere.

For both temperature and water vapor, one has to be aware of differences in models and processing techniques used at different locations. In spite of these considerations, radiosondes have a large impact on numerical models, are available in large quantities, and sample the full range of conditions found on planet earth. It is difficult to think of anther observation that has the same sample size and coverage.

Another of the problems with radiosondes is that there may be a time difference between the satellite and the sonde. This has the largest effect near the surface where the diurnal change in temperature can approach 30 K. Over some regions, hourly surface observations are available, and we are investigating the possibility of using these observations to increase the accuracy. Our plan is to use the hourly surface observations to determine the change in temperature between the two times, and use this as a predictor of the retrieval error near the surface. If there is an improvement, then a diurnal model can be developed based on local time, and this can be used to improve the accuracy.

There are other sources of data for validation. For example, commercial aircraft measure profiles near airports, some sites are using radar acoustical sounders, and others are using lasers. The analysis used by numerical models have some advantages and disadvantages. They are probably the only way to use aircraft reports. Aircraft ascend and descend slowly, so the upper level soundings are available at great distances from the airport. However, given the large number of soundings, the analysis near an airport should be very accurate. But some users may not want to use a value derived from an analysis by one particular center. Our approach is to utilize as much of the information available at the NCEP and the Goddard DAO as possible.

Although the value of campaigns is limited by the limited sample size, the concept of having a few, well instrumented sites to take observations at the time of satellite over pass has a lot of appeal. Such a site should be located in an area of uniform surface temperature and elevation, the surface skin temperature should be monitored, and instruments for monitoring the atmospheric parameters such as temperature, moisture, and trace gases should be assembled. Several sites should be set up and they should cover a range of atmospheric conditions. A suite of such instruments on a ship would be extremely valuable, and ship could be a research vessel doing other work. This is similar to the current use of ships of opportunity for radiosonde observations.

The AIRS initial validation of geophysical products uses an intensive campaign of radiosonde launches from major meteorological research sites around the globe, coordinated with EOS PM overflights starts about 4 month after launch. We have currently identified three such sites, ARM sites in Oklahoma, Alaska's North slope and the Southwest pacific. We are discussing support from ARM equivalent sites in Brazil, Australia, and China. The campaign is planned to last for about three months, starting four month after launch, i.e. April - July 2001. The radiosonde launches are primarily intended to validate the AIRS water vapor retrievals. The launch of research grade radiosondes during the uplooking infrared radiometer/spectrometer and frost-point hydrometer.

AIRS encourages the development of an Advanced Global Moisture Sounding Network starting from 4-6 of the GEWEX global radiosonde sites. In addition to high-quality radiosondes, these sites should be further equipped with advanced, ground-based moisture sounding instrumentation. Such instrumentation should include, at least, a DIAL or Raman LIDAR, an up-looking high resolution IR spectrometer/sounder (such as the University of Wisconsin AERI), a passive microwave sounder, and a high-quality GPS receiver. The DOE ARM sites are logical choices for three of these sites: North Central Oklahoma, USA; tropical western Pacific; and Alaskan North Slope. Additional sites could be located in South America, Australia, Africa, Antarctica, the Indian Ocean (e.g., Island of Diego Garcia), etc., thereby providing a global distribution. Assistance from foreign countries should be solicited for these sites (Italy, Germany, France, Japan, etc.). Every effort should be made to include a mix of ocean and land locations for these sites. Although as previously discussed, for the purposes of H_2O validation, there are several advantages to using ocean sites for the base of operations in validation campaigns.

Other radiosondes of interest are the ozonesondes for ozone validation.

4.3.3 Cross validation with other instruments

<u>MODIS</u>

The Moderate Resolution Imaging Spectroradiometer (MODIS) is due for launch in mid-1998 on the EOS AM-1 platform. MODIS will also be aboard the PM-1 platform providing radiometric measurements which are time and space coincident with the AIRS. MODIS possesses 36 spectral channels with 16 bands in the 3.8 to 14.4 μm interval. MODIS on PM-1 is expected to have a comparable radiometric performance to MODIS on AM-1 with NEΔT values typically 0.05 to 0.25. Where appropriate spectral coverage permits, the comparison of the performance of MODIS and AIRS will offer considerable benefit. While it will be necessary to account for the different spectral and spatial resolutions of the sensors, there will be the added benefit of two high quality radiometric sensors on the one platform simultaneously viewing Earth scenes.

The differences in the instantaneous FOVs suggest that there will be the most benefit for comparisons for validation purposes being made over uniform targets, although MODIS data can be spatially convolved using the AIRS spatial response function. In that sense the ocean and uniform clouds offer the opportunity to compare two AIRS products, namely SST and cloud top temperature for warm and cold scenes respectively. AIRS data, being at higher spectral resolution, will need to be convolved with the MODIS filter functions to implement the comparison.

Such comparisons could be made routinely as part of a longer term validation of both instrument and algorithm performance. Additionally, there would be benefit in coordinating such comparisons with the high altitude aircraft validation campaigns using the NAST, as well as a high spatial resolution imager (i.e., MAS) and the Cloud LIDAR System (CLS). The NAST is a high resolution interferometer designed with excellent radiometric and spectral calibration, and with a spectral resolution superior to either of the on-orbit instruments (AIRS and MODIS). A high spatial resolution imager (MAS) will aid preferred scene identification and the correct registration of the FOVs of the various sensors. The airborne cloud LIDAR system will assist in the selection of suitable cloud targets (opaque and uniform cover) as well as fixing the cloud height to support the associated radiative transfer calculations. The approaches recommended for the airborne validation campaign are being evaluated in the SUCCESS field campaign.

<u>MODIS and the AIRS Visible/Near-IR Channels</u>

MODIS data may be used to improve the calibration of AIRS VIS channels. The same techniques can be used to validate VIS radiances. The approach being considered is to use several narrow MODIS channels to synthesize the spectral response of the broader VIS channels, and then spatially convolve the MODIS data to match the larger pixel size of VIS. Table 4.1 shows the overlapping VIS and MODIS channels to be used in this procedure.

TABLE 4.1: Related VIS and MODIS channels

VIS Channel 1, 0.40 to 0.44 micron

MODIS Channel	Wavelength Range (micron)
8	0.405 to 0.420
9	0.438 to 0.448

VIS Channel 2, 0.58 to 0.68 micron

MODIS Channel	Wavelength Range (micron)
1	0.620 to 0.670
14	0.673 to 0.683
19*	0.915 to 0.965

*Because AIRS Channel 2 contains water vapor absorption bands which are not in MODIS 1 and 14, MODIS Channel 19 is included.

VIS Channel 3, 0.71 to 0.96 micron

MODIS Channel	Wavelength Range (micron)
15 2 19	0.743 to 0.753 0.841 to 0.876 0.915 to 0.965

VIS Channel 4, 0.45 to 0.95 micron

MODIS Channel	Wavelength Range (micron)
8 3 4 1 15 2 19	0.405 to 0.420 0.459 to 0.479 0.545 to 0.565 0.620 to 0.670 0.743 to 0.753 0.841 to 0.876 0.915 to 0.965

Each VIS channel can be considered a linear combination of the listed MODIS channels, with coefficients determined by model and in-flight data analysis. Preliminary work, presented in Aumann et al. (1996), indicates that this approach can work well for VIS Channels 1 and 4, using desert and semi-desert ground targets. For VIS Channels 2 and 3, only unvegetated desert (such as White Sands, New Mexico) should be used.

For this technique, VIS and MODIS data should be coregistered to a fraction of a VIS pixel (although using relatively homogeneous surface targets can relax this requirement). MODIS pre-launch instrument characterization is already at this level, while in-flight geolocation algorithms described in section 4.3, which rely on observations of known ground features, will do the same for VIS.

AVHRR

The Advanced Very High Resolution Radiometer (AVHRR) is a broad-band, five channel imager sensing in the visible, near-IR, and thermal-IR regions. It is carried by NOAA polar orbiting satellites. AIRS VIS channels 2 and 3 are designed to be similar to AVHRR channels 1 and 2, making cross validation straightforward. The table below compares these two channels for the two instruments.

Instrument/Channel	**Nadir Resolution (km)**	**Spectral Range (micron)**
AVHRR 1	1.1	0.58 to 0.68
VIS 2	2.3	0.58 to 0.68
AVHRR 2	1.1	0.73 to 1.10
VIS 3	2.3	0.71 to 0.95

AMSR

The Advanced Microwave Scanning Radiometer (AMSR) is part of the EOS-PM1 payload. As such it offers an opportunity for near simultaneous and collocated cross-validation. It is a conically scanning imaging radiometer similar to SSM/I, but with a wider spectral coverage (6.9 to 89 GHz vs. 19 to 85 GHz), smaller IFOV (0.4° vs. 1.1° at 37 GHz), and denser sampling (10 km x 10 km vs. 25 km x 25 km at the lower frequencies). The active Earth scan consists of a ±61° sector of the scan cone in the forward direction, with a constant angle of incidence of 55° (the nadir angle is 47.4°). While AMSR traces its principle of measurement as well as retrieval algorithms to SSM/I, in the EOS-PM1 time frame nearly identical instruments will have been operated on TRMM (from 1997) and ADEOS-2 (from 1999). It may therefore be a fairly well validated instrument even before launch.

Of particular interest in the present context are the AMSR channels at 23.8 GHz and 89 GHz, coinciding with AMSU-A channels 1 and 15. Since AMSR measures two orthogonal polarizations at each frequency, the corresponding AMSU-A single polarization can be synthesized. This will make it possible to perform cross-validation of brightness temperatures at these two frequencies, by synthesizing AMSU-A footprints from a number of the much smaller AMSR footprints near the AMSU-A swath edges, where the angles of incidence are nearly equal.

We will also carry out cross-validation of geophysical products, such as rain rate, snow/ice flag, cloud liquid water and precipitable water content. In addition, AMSR-derived surface parameters will be used to validate portions of the microwave processing algorithms.

CERES

CERES offers an opportunity to cross-validate the AIRS integrated infrared spectra by comparison with the CERES outgoing total and clear infrared products. Since AIRS does not cover the complete range of frequencies that CERES does, we will use the AIRS level 2 products to compute the outgoing radiances and compare on a monthly or weekly basis depending which is more appropriate. This type of comparison will be very useful for geographic isolation of possible long-term biases and other irregularities in the AIRS products.

NOAA AMSU-A/B

NOAA-K, which is to be launched in early 1998, will carry the first flight models of AMSU-A and AMSU-B (which is nearly identical to HSB) and is expected to still be in operation when EOS-PM1 is launched in 2000. This offers some opportunities or cross validation, especially at orbit crossover points. However, NOAA-K will be in a morning orbit, and there will be a substantial time lag between NOAA-K coverage and EOS-PM1 coverage.

The next NOAA polar platform, NOAA-L, will be launched into an afternoon orbit, however, similar to the EOS-PM orbit. It will also carry the AMSU instruments. It is possible that NOAA-L will be launched in the same time frame as EOS-PM1. If that happens, a much better cross validation scenario would exist. This can not be predicted at the time of this writing, but it is our intention to take full advantage of such an opportunity, should it present itself.

Other Opportunities

There are other very important sources for cross validation of AIRS products. These include other instruments such as SBUV, TOMS, GOME (or whatever follow-ons are available) for ozone. The European and Japanese agencies will also be active in space-based atmospheric monitoring and it is hoped that active collaborations will be maintained.

4.3.4 Spatial Calibration and Validation

The AIRS instrument pointing model and geolocation algorithms can be validated and refined using observations of known surface features during normal instrument operations. This technique is described more fully in Jovanovic′ and Hofstadter (1997). (Though written for the VIS channels, it is applicable to the IR and microwave as well.) The approach is to assemble a data base of Ground Control Points (GCP's), which are easily located in a data set, and for which extremely accurate geocentric positions are known. By locating the GCP's in an image, and comparing their calculated geocentric positions with their known locations, the instrument pointing can be validated or refined.

An example of how this technique might be used is to start with five input data sets: spacecraft orbit data, an Earth model, an instrument model (including a covariance matrix for components of the instrument model), an image from the instrument to be validated, and a set of GCP points for the region being imaged. The procedure is then as follows.

1. Locate the GCP's in the image data. This is done in three steps. First, area-based matching algorithms are applied, which are then refined with a feature-based matching technique. If necessary, interactive measurements by a human operator can then be applied if the automated techniques fail to locate enough GCP's.
2. The current instrument model is then used to calculate the geolocation of the image pixels associated with each GCP. The known GCP location is compared to the calculated one. If they are in agreement, the instrument model is validated.
3. If the calculated geolocations do not match the known locations, the instrument model can be updated using a least-squares regression to bring the observed and *a priori* locations into agreement.

Islands and shorelines represent a suitable collection of GCP's, and the SeaWiFS project has collected a World Vector Shoreline data base containing the necessary information. The MODIS instrument has already begun exploring the accuracy and usefulness of this data for geolocation purposes at a higher spatial resolution than will be needed by AIRS.

For the microwave instruments two approaches will be used. The first takes advantage of the special "stare mode", where the scan mirror is halted, so that the antenna stares in one direction (usually nadir) for some time, while a coast line or other known surface feature with a sharp step in brightness (i.e. emissivity and/or temperature) is crossed. This makes it possible to calibrate the pointing in the direction perpendicular to an edge feature with an accuracy similar to the specified instrument pointing accuracy.

The second approach is to build up a global map of coast lines over an extended period of time (i.e. many orbits). As data accumulates, the fuzziness of this map due to the coarse sampling and fuzzy antenna pattern will be reduced until only the contribution from pointing instabilities remain. From features in this map GCP’s can be identified and used as described above to determine pointing biases.

Special situations, such as a very oblique coastline crossing, will also be taken advantage of to estimate pointing errors.

4.4 Model Verification of AIRS products

The use of AIRS/AMSU-A in the NCEP system builds upon the extensive experience acquired with the operational use of HIRS/MSU. The direct assimilation of radiances, with a forward model that gives a very good first guess of what the expected radiances should be, currently provides a very powerful tool for validation of the HIRS/MSU data, and will be equally useful in validating AIRS data. In this section we will first describe the procedures followed with HIRS/MSU operational data, and then the changes that will be required for the AIRS applications.

In NCEP's variational assimilation of HIRS/MSU radiances, the global atmospheric 6 hour forecast (which is generally an excellent estimate of the state of the atmosphere) is interpolated to the observation location, and a forward radiative transfer model converts the model profile of temperature and moisture (plus estimates of the surface temperature and total ozone) into simulated clear column radiances for each channel (Derber and Wu, 1996, 1997). It is important to note that the first guess can provide a perfect collocation for every observation.

The ability to compare every observed radiance for each channel with a simulated measurement collocated in space and time is an essential tool for validation of the HIRS/MSU (or AIRS/AMSU-A) data. This includes estimations of the biases and the standard deviations of the fits between observed and calculated radiances (which include the errors of the AIRS measurement, the forecast used as a first guess, and the forward model used to construct the simulated radiances). These deviations (bias and standard deviations) can be averaged over geographical bins (e.g., 0.5 degree or 1 degree squares) or as a function of scan angle, etc., and accumulated over time. Because the biases and data rejection rates from the Quality Control (QC) are available on both geographical and orbital distribution, it is easy to perform time averages that can point out patterns of errors dependent on factors such as orbital parameters, land-sea, SST, surface temperature, etc.

With the input of the observed minus simulated radiances, it is possible to obtain the geographical distribution of the biases for each channel, or estimate them as a function of the scan angle, zenith angle, estimated cloud cover, land, ocean, different surface covers, etc., and similarly for the standard deviation. The experience at NCEP is that problems with biases and/or instrument or algorithm problems become very apparent when the data deviation from the radiance first guess is plotted either geographically or orbit by orbit, or by scan angle, etc. In fact, the availability of the radiances first guess is allowing NCEP and ECMWF to consider the direct use of level 1-B HIRS/MSU radiances rather than the cloud cleared radiances as presently done (research currently done by Tony McNally, a visitor from ECMWF at NCEP), since the additional information allows the detection of problems with cloud clearing algorithms not apparent with the standard approach.

Currently there are significant biases observed between the simulated and observed HIRS/MSU brightness temperatures. These biases can be due to instrument calibration problems, the ground processing of the data, inaccuracies of the forward model, or biases in the atmospheric forecast model. To remove the spatially dependent biases, a bias correction is built within the NCEP variational analysis system. As predictors of the bias, Derber and Wu have chosen the values of a constant term, MSU channels 2-4, HIRS channel 1, the solar zenith angle, and its square. These predictors are multiplied by a set of coefficients to produce the bias correction. The coefficients are generated by augmenting the vector of the analysis variables with the bias coefficients and solving them along with the rest of the analysis variables. A similar procedure can be developed for AIRS, and the monitoring of the bias corrections will also provide a validation tool to the AIRS team.

The assimilation of AIRS data will probably require major data compression, since the number of channels available (over 2000) is two orders of magnitude larger than the number of HIRS/MSU channels. It may be possible that by the time AIRS is launched, NCEP may be able to handle all the channels, or a number of observations one order of magnitude smaller (order of 200). After those "superchannels" are selected, NCEP will require an accurate forward model to go from temperature and moisture profiles and other ancillary data to simulated superchannels brightness temperatures. A linear tangent model and adjoint (transpose) of the forward models will be also required. However, the use of superchannels which combine data from several individual channels will also require some "unscrambling" of their errors. Again, it is expected that problems with AIRS data will become quite apparent when the differences with the first guess radiances are appropriately displayed, even if they come from superchannels. After that, our expectation is that the same problems will be apparent from individual channels corresponding to a superchannel even over single orbits.

As is the case for TOVS, the three dimensional variational assimilation (3DVAR) of the radiances will result in estimates of biases and quality control data that will be immediately available to guide the validation and improvement of the forward algorithm. These, and other QC data such as rejection rates, should prove very useful for validating the models, and after operational implementation, to monitor improvements in the algorithms.

4.5 AIRS Launch Validation Timeline.

There are specific tasks that can be done while the AIRS/AMSU-A/HSB hardware slowly comes up to is full capability and in the presence of many interruptions from external events. Given these limitations specific tests can be phased in as the capability of the hardware is understood and stabilizes.

Hardware status	Time	Data availability and status	Specific analysis tasks
Prelaunch			Aircraft Flights, NOAA K, DMSP, etc.
Software launch readiness review	L-6		Validation software tested using simulated AIRS data
Launch	L		
AMSU-A and HSB opens	L+0.5		
AIRS opens	L+1	Viewable VIS data 1 day after opening, Viewable IR spectra 3 days after opening. Use pre-launch radiometric and spectral calibration software. Channel frequencies calculated from upwelling spectral radiance Level 1b standard frequency output = OFF Level 1b and level 2 data valid flags set = FALSE	AMSU-A/HSB validation following NOAA K procedures. TLSCF: Slantpath corrected microwave quicklook images. TLSCF: Slantpath corrected visible quicklook images Slantpath corrected infrared quicklook images (HIRS equivalent channels). Compare qualitatively with experience from NOAA K Retrievals with HIRS3 equivalent channels, AMSU-A and HSB. Compare with collocated radiosondes.
MODIS opens	L+1.5		
Review	L+2.5	Review preliminary in-orbit performance	
	L+2.5	Spectral Calibration stable, except for major maneuvers, like cold space view maneuver. Define preliminary	Verify frequency calibration stability using ARM overflight data (slow forward algorithm) Verify frequency calibration and shifting

		standard frequency set and output standard set.	procedure. Verify Spatial calibration stability of IR using coastline crossing.
Cold Space View Maneuver	L+3		
	L+3.2	Radiometric Calibration stable one day after cold space maneuver, spectral calibration stable after 2 days.	Re-verify frequency calibration and shifting procedure.
Review	L+3.5	Official in-orbit instrument performance review. Preliminary review of science performance. Define standard Frequency set. Level 1b standard frequency output = ON	Recalculate the Rapid forward algorithm for standard freq. Set Re-verify spatial calibration of IR using coastline crossing.
Start of data product validation	L+4	Level 1b data valid flags set = TRUE Matchup statistics=ON, but not applied (Tuning=OFF) BUAN data set available from L+4 to L+8. Duration of this period is determined by the number BUAN data sites. We are assuming 20 sites @ two passes per day = 4000 BUAN matchups. Expect 20/40/40 split clear/clearable/cloudy	Start generation of global matchup statistics. Validate window and sounding channel radiometry for clear cases using GCM for day/night/ocean/land cases. (About 30 AIRS channels) Validate first product algorithm relative to BUAN data. Clear fields first, then cloudy fields. Validate final product algorithm relative to BUAN data. Clear fields first, then cloudy. Validate cloud clearing as function of ocean/land/day/night, eta and cloud fraction. Validate cloud-cleared radiances using 1 in 9 clear field approach at ARM site.

	L+7	Aircraft underflight at L+7 MODIS data assumed to be available	AIRS-HIS radiometric performance validation for clear condition Validate AIRS radiometric performance relative to synthetic MODIS footprints Validate AIRS cloud cleared product using MODIS cloud mask hole finder Validate final product algorithm relative to BUAN data with collocated tuning adjustments. Clear fields first, then cloudy.
Review	L+8	Update level 1 and level 2 software from pre-launch version at EOSDIS Collocated Radiosonde tuning = ON Level 2 data products valid flag = TRUE	
Routine operations start			Start validation of research products: Cloud characterization, MODIS, CERES, AMSR cross-calibration

L+x means launch date plus x months.

BUAN is the Baseline Upper Air Network of radiosonde launches coincident with the EOS-PM overflight.

The level 1b and level 2 data valid flag is probably a 16 bit word, where each bit is set to TRUE as validation passes certain gates. Software at the TLC is able to process partially valid data, while software at EOSDIS can process only fully valid data.

5.0 Implementation of Validation Results in Data Production

5.1 Approach

The AIRS validation data stream, as described in figure 5.1, comes from four major sources: Instrument data, 10% of the science data, subset file data, and the field campaign data. Instrument data is necessary for instrument health and long-term trend analysis. The requirement for 10% of the science data is aimed primarily at long term parameter monitoring as described in 4.3 and for algorithm testing, error assessment, and development. The subset data will be used for parameter monitoring on a shorter term basis. The field campaign data is a more temporally irregular data source and is expected to be small. Other ancillary validation data sets, such as the MODIS cloud mask, have not yet been included due to unknown expected frequency of usage.

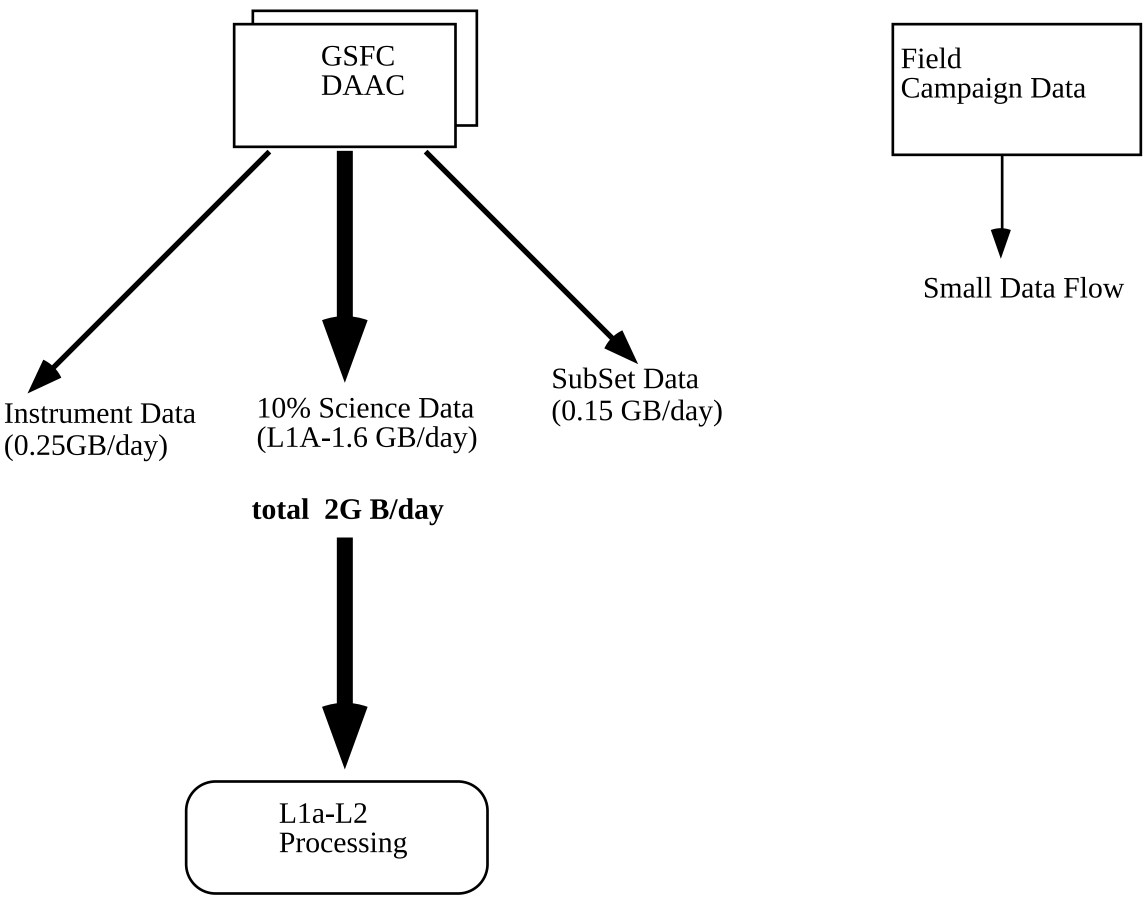


FIGURE 5.1 TOTAL INPUT DATA STREAM

<u>Subset Files</u>

The approach taken by the AIRS team is to combine the browse/subset processing and the validation data output into one PGE. The AIRS Processing PGE Produces Subset Data Files containing Level 1B and Level 2 data on per-Granule Basis

- A new Subset Data File is written for each granule
- L1B and L2 Subset Data are written for each AMSU-A footprint
- The Subset Data volume amounts to 9.75 MB/orbit or 142 MB/day, which is less than 5% of the volume of the L2 Products

AIRS Validation Effort and follow-on Quality Assurance at TLSCF will utilize the Subset Data Files, which provide condensed data sets for

- generation of quick-look
- identification of AMSU-A footprints which should be examined in detail based upon retrieval quality flags
- correlation of retrieval end states with retrieval flags and other parameters

Allows standalone programs at TLSCF to use Subset Data Files for instrument startup, Quality Assurance and Validation.

The Processing PGE (executing at the DAAC) will produce Subset Data files (one each per granule) containing Level 1B and Level 2 data for each AMSU-A footprint. These Subset Data files (amounting to 150 MB/day) will be transferred to the TLSCF for archival and will be used for Validation and Data Quality Assurance.

The Subset Data File will contain the following:

- Time, Positions (AMSU-A footprint and included HSB and AIRS spots), Slant Angle (view path from s/c to footprint on surface)
- Calibrated Radiances, converted to brightness temperatures, of selected AIRS channels for each of the 9 included AIRS spots in each AMSU-A footprint
  - 1 window channel
  - 4 temperature sounding channels
- Calibrated Cloud-Cleared Radiances, converted to brightness temperatures, of selected AIRS channels used for retrievals
  - 4 window channels
  - 6 temperature profile channels
  - 4 water vapor profile channels
  - 1 ozone channel
- 8 selected AMSU-A channels
- 4 HSB channels for each of the 9 included HSB spots in an AMSU-A footprint
- Retrieved cloud parameters
- Retrieved surface parameters
- Retrieved water vapor burden
- Retrieved ozone burden
- Retrieved temperature profile (9 slabs)
- Retrieved moisture profile (4 slabs)
- MW first guess liquid water burden and rain rate
- VIS low cloud and variability indices

FILE: AIRS_SUBSET

Item	Size (bytes)	Comments
Time of Observation	8	continuous SI seconds since midnight UTC 1/1/93 (Toolkit Internal Time, TAI)
Year of Observation	2	integer (4 digits, i.e. 2001)
Month of Observation	2	integer (1->12)
Day of Observation	2	integer (1->31)
Orbit Number of Observation	2	integer (1->15)
Scan Set Number of Observation	2	integer (1->750)
Scan Line Number of Observation	2	integer (1->3)
AMSU-A Footprint Number of Observation	2	integer (1->30)
Latitude (of AMSU-A footprint on surface)	2	integer, 10^{-1} degree
Longitude (of AMSU-A footprint on surface)	2	integer, 10^{-1} degree
Slant Angle (view path to AMSU-A fp on surf)	2	integer, 10^{-1} degree
Latitude Array (9 HSB spots on surface)	2*9	integer, 10^{-1} degree
Longitude Array (9 HSB spots on surface)	2*9	integer, 10^{-1} degree
Latitude Array (9 AIRS spots on surface)	2*9	integer, 10^{-1} degree
Longitude Array (9 AIRS spots on surface)	2*9	integer, 10^{-1} degree
AMSU-A Channel Array (8 chan in footprint)	2*8	integer, 10^{-1} K, converted to T_B
HSB Channel Array (4 chan in 9 spots)	2*4*9	integer, 10^{-1} K, converted to T_B
AIRS window chan Cldy Rad Array (9 spots)	2*9	integer, 10^{-1} K, converted to T_B
AIRS T chan Cldy Rad Array (9 spots * 4 ch)	2*4*9	integer, 10^{-1} K, converted to T_B
MW Retrieval Flag Array	2	16 1 bit flags
AIRS Retrieval Flag Array	2	16 1 bit flags
AMSU-A Residual	2	integer, 10^{-3} K, rms
HSB Residual	2	integer, 10^{-3} K, rms
AIRS Temperature Profile Residual	2	integer, 10^{-3} K, rms
AIRS Water Vapor Profile Residual	2	integer, 10^{-3} gm cm^{-2}, rms
AIRS O_3 Profile Residual	2	integer, 10^{-2} Dobson Units, rms
AIRS Surface Temperature Residual	2	integer, 10^{-1} K, rms
AIRS Clr Radiance T channel Array (6 ch)	2*6	integer, 10^{-1} K, converted to T_B
AIRS Clr Radiance H_2O channel Array (4 ch)	2*4	integer, 10^{-1} K, converted to T_B
AIRS Clr Radiance (O_3 channel)	2	integer, 10^{-1} K, converted to T_B
AIRS Clr Radiance T_{surf} channel Array (4 ch)	2*4	integer, 10^{-1} K, converted to T_B
AIRS Cloud Percentage	2	integer, $0 \leq$ Percentage ≤ 100
AIRS Cloud Top Pressure	2	integer, 10^{-1} mb
Retrieved Surface Temperature	2	integer, 10^{-1} K
Retrieved Total Water Vapor Burden	2	integer, 10^{-3} gm cm^{-2}
Retrieved Total Liquid Water Burden	2	integer, 10^{-3} gm cm^{-2}
Retrieved Total O_3 Burden	2	integer, 10^{-1} Dobson Units
Retrieved Temperature Profile Array (9 slabs)	2*9	integer, 10^{-1} K
Retrieved Water Vapor Profile Array (4 slabs)	2*4	integer, 10^{-3} gm cm^{-2}
MW First Guess Total Liquid Water	2	integer, 10^{-3} gm cm^{-2}
MW Rain Rate	2	integer, 10^{-3} mm hr^{-1}
VIS % containing low clouds Array	2*9	integer, $0 \leq$ Percentage ≤ 100
VIS % containing no low clouds Array	2*9	integer, $0 \leq$ Percentage ≤ 100
VIS Variability Index Array (all columns)	2*9	integer, 10^{-3} unitless, rms
VIS Variability Index Array (clear columns)	2*9	integer, 10^{-3} unitless, rms

5.2 Plans for archival of validation data

The AIRS TLSCF validation data set will be archived at the AIRS TLSCF at the Jet Propulsion Laboratory using a commercial data base. The data set will be archived as an integrated data set with links to EOS satellite, aircraft and in-situ validation data sets. There will be a set of I/O filters attached to the database in order that the data being accessed can be delivered in a multitude of formats, i.e., ASCII tabular, IEEE binary, HDF-EOS, etc.. In addition to format filters there will also be subsetting filters to allow a range of subsetting options for access to the data set. If the validation data reside elsewhere (i.e., Oak Ridge DAAC),the local TLSCF database shall provide the necessary links to that dataset, but will not provide filters, those data will be accessed in native format without subsetting and it will be up to the user to translate, read and subset the data. All data stored at the TLSCF and available for dissemination will have the necessary metadata attached in keeping with EOS data policy.

5.3 Data management requirements/validation tool development

The main goal of the validation tools is ready access to and analysis of level 1 and 2 data. These data are central to retrieval validation, and have similar geometry. Access will be made possible by storing approximately 10% of these in a data warehouse for easy user access. The data will be structured to enable the simultaneous access to all information pertaining to a single retrieval. This information will include retrieved profile, cloud and surface properties, the radiances from which they were retrieved, and any associated correlative observations such as collocated radiosondes. Figure 5.2 illustrates schematically the relationship between retrievals and the cloud-cleared AIRS radiances appropriate to the retrieval. Not illustrated is the complexity of the data: the retrievals will also include ozone profiles and cloud and surface parameters. The radiances will include spectra from one AMSU-A footprint, nine AIRS and HSB footprints each, and 54 visible footprints per AIRS footprint. The cloud-cleared AIRS spectra will also be duplicated as residuals of observed minus calculated radiances. The on-planet geometry of the radiances is shown in Figure 5.3. The large, nearly hidden circle depicts one AMSU-A footprint, the nine smaller circles depict the AIRS and HSB footprints, and the grid represents the visible channels. The bold rectangle at the upper left shows the 54 visible pixels associated with each AIRS / HSB footprint. There is a half-pixel mismatch in overlapping visible scans. These radiance, along with associated retrieved quantities, will comprise the basic data unit in the validation database.

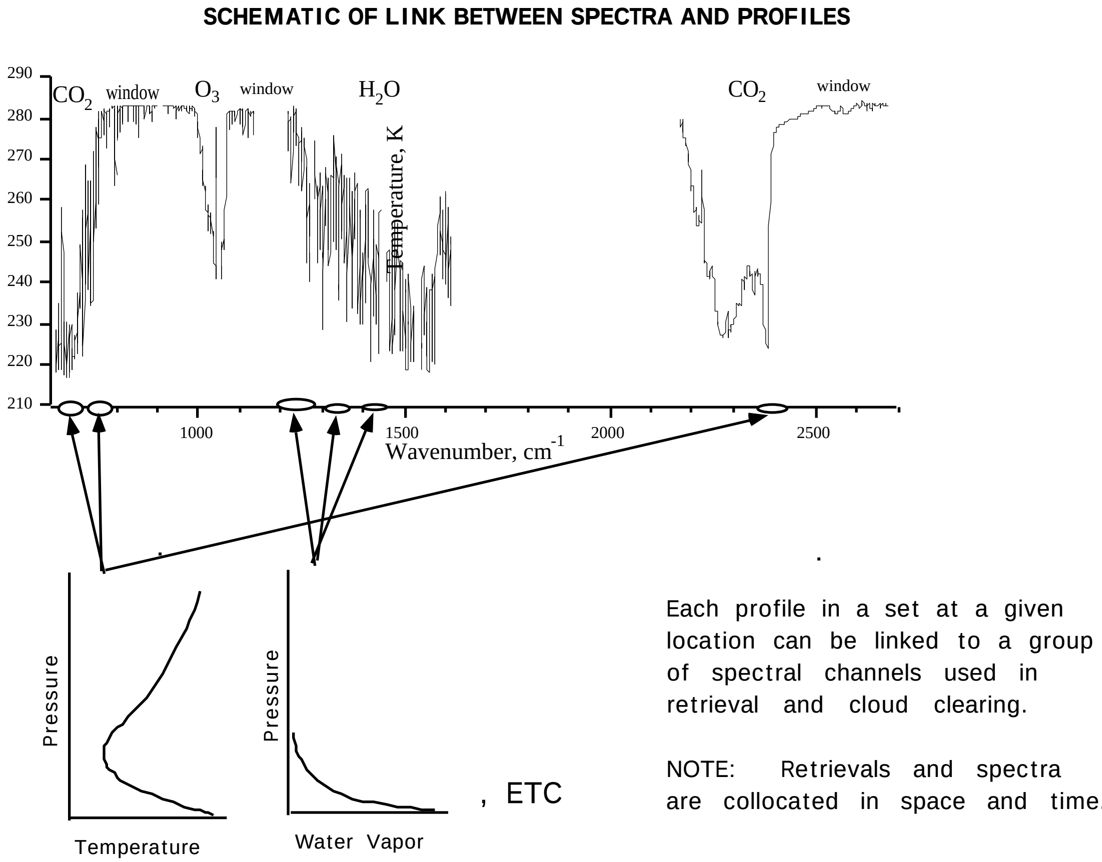


FIGURE5.2. SCHEMATICLEVEL1B ANDLEVEL2 DATA LINK

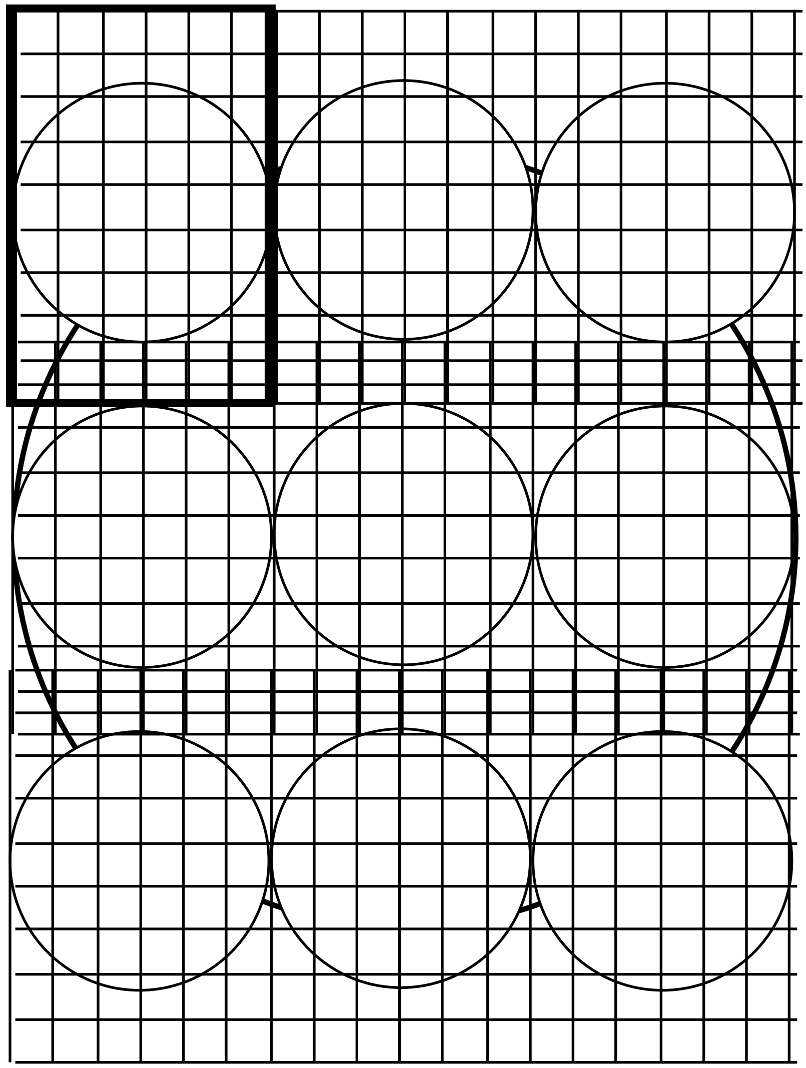


FIGURE 5.3. THIS DIAGRAM ILLUSTRATES THE SOUNDING GEOMETRY AT THE SUBSATELLITE POINT.

Figure 5.4 shows the basic data elements, and their place in the retrieval stream. Software tools have been written to analyze this dataset at several levels. Direct comparisons can be made of ‘truth’ and retrieved quantities on a profile-by-profile basis. Also being developed is the ability to examine retrieved quantities and any or all radiances associated with them. At a higher level of complexity, cross sections of retrieved and radiance quantities will be accessible to the user. Additionally, cross sectional displays of truth and residual fields can be plotted. These cross-sections may be chosen both along and across the orbit track. Software tools also exist to analyze several orbits’ data. These tools generate maps of specified quantities by filling data void using several interpolation methods. This ability to analyze data blocks varying in size from one profile to several orbits is central to the validation software design philosophy.

Components of the basic AIRS validation data element

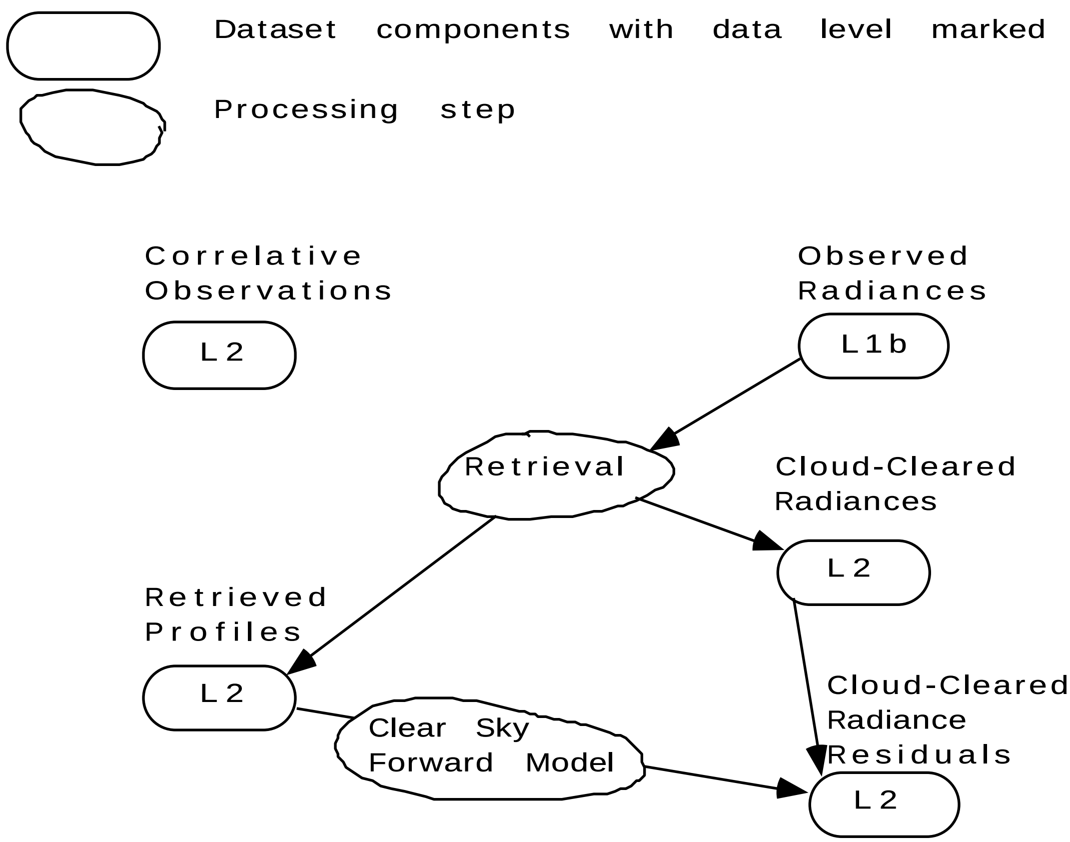


FIGURE 5.4 VALIDATION DATA COMPONENTS.

5.3.1 Validation Data Warehouse Architecture

The validation data warehouse system, showing in Figure 5.5, is built using the Metadata database as its center. This central database contains catalog of product characteristics, directories of product inventory, and reference links to product data storage location. Three additional components were added to support other data warehouse functions:

- **Data Agents**: responsible for shipping/Receiving of data products;
- **Storage Subsystem**: managing on-line and near-line data storage;
- **Access Interfaces**: providing application and user access to data products.

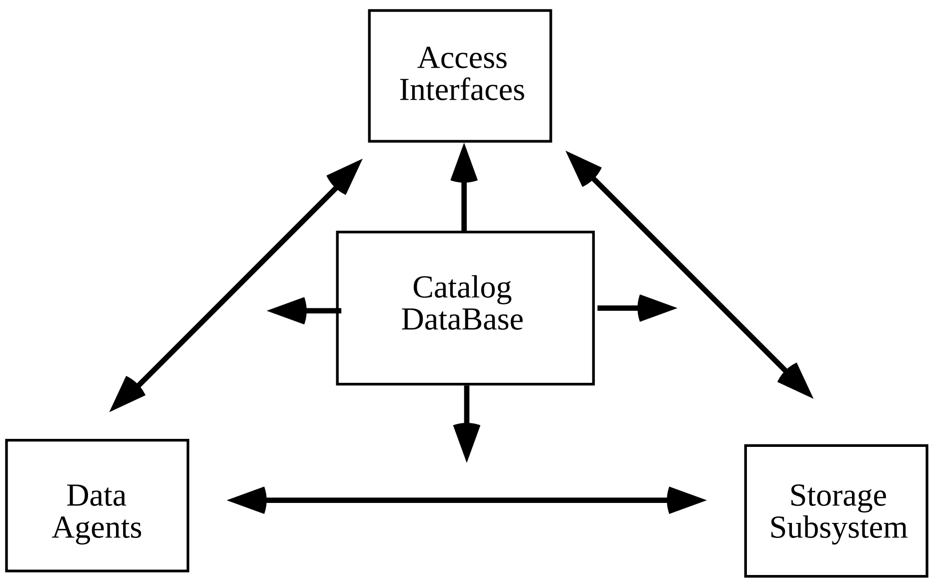


FIGURE 5.5. VALIDATION DATA WAREHOUSE ARCHITECTURE

Detailed design description for each of the four major warehouse components is presented in the following subsections. The current implementation status of the overall data warehouse system is giving in the last section of this document.

5.3.2 Schema and Catalog Database

The primary function of the schema and catalog database is to allow users and user applications to search for data products using queries, locate references to specific data products, and retrieve requested product data from the data warehouse. This function will be provided using a set of database query/access interfaces. Higher level Graphic User

Interface (GUI) and Application Program Interface (API) built upon the base interface will also be provided.

In addition to its primary functions, the central database is also used to control and synchronize the overall operation of the validation data warehouse. As shown in figure 4 below, the Catalog Database provides three additional control interfaces.

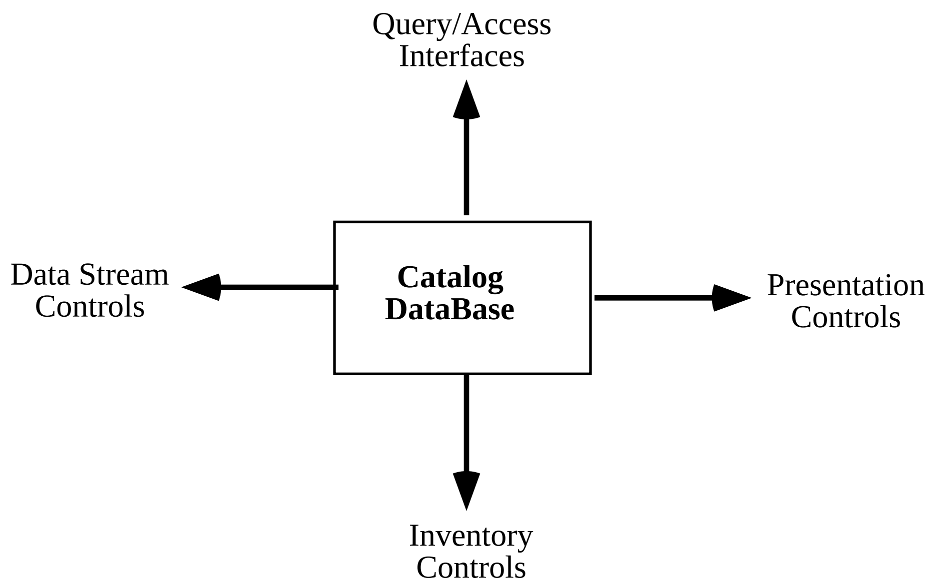


FIGURE 5.6. SCHEMA AND CATALOG DATABASE INTERFACES

- **Data Stream Controls** --- A set of monitor and control interfaces for setting up and controlling the operation of external input/output data streams connected to the data warehouse.
- **Inventory Controls** --- A set of monitor and control interfaces for monitoring the movement of external data products into and out of the storage subsystem of the data warehouse.
- **Presentation Controls** – A set of monitor and control interfaces for retrieving product data from the storage subsystem according user specified presentation requirements, e.g., format conversion, subsetting, or merging.
- **Query/Access Interfaces** --- A set of database query interfaces based on the standard SQL interface extended with Object-Oriented extension provided by the database.

5.3.3 Shipping/Receiving Data Agents

The shipping/receiving data agents, shown in Figure 5.7, are autonomous programs set up to handle external data streams connected to the data warehouse. A "**data stream**" is a continuous data connection that either feeds data into or receives data from the warehouse periodically or asynchronously. Upon receiving timer events or external data available events, the agent programs will be invoked to interact with external data sources/targets. These agent programs are also responsible for internal movement of data products to and from the storage subsystem utilizing the Inventory Control Interface.

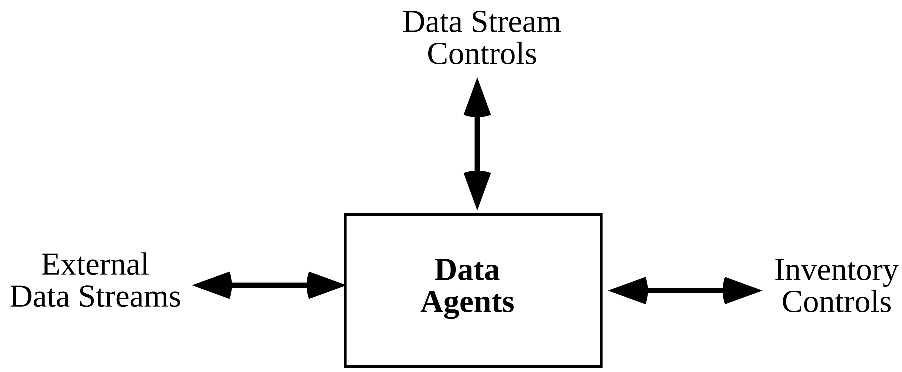


FIGURE 5.7 SHIPPING/RECEIVING DATA AGENTS

The data agents are set up and controlled using the Data Stream Control Interface. Depending on the interaction characteristics of external data stream, the user can choose from two types of agent program provided by the system:

〈 **Periodic Data Stream Agent** --- This is a program activated periodically based on users specified activation frequency. It is usually set up as a "cron" job triggered by the system clock.

〈 **Asynchronous Data Stream Agent** --- This is a program activated asynchronously upon receiving data available signal from users specified data ports.

The warehouse will support two different types of data transfer mode: **Push** and **Pull**. In the push mode, data will be pushed from the sender to the receiver. In the pull mode, data will be pull by the receiver from the sender. Periodic Data Stream Agents can be set up to operate in both modes. On the other hand, Asynchronous Data Stream Agents can only be operated in the push mode.

The warehouse will support several standard data transport protocols used to transfer data between data agents and external data sources/targets. Key protocols include:

〈 **FTP**: the standard file transfer protocol;
〈 **HTTP**: the WWW based data transfer protocol;
〈 **SMTP**: the standard email based data transfer protocol.

5.3.4 On-line and Near-line Storage Subsystem

The on-line and near-line storage subsystem, show in Figure 5.8, is responsible for managing physical data product storage locations. The physical storage location information will be used as "**References**" to the data product in the Catalog Database.

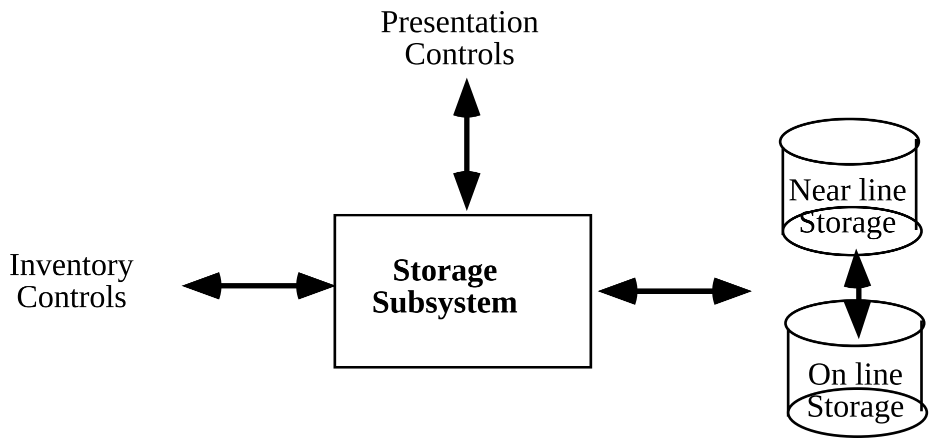


FIGURE 5.8. ON-LINE AND NEAR-LINE STORAGE SUBSYSTEM

Due differences on the size and usage characteristics among data products to be stored, several different types of data storage technology will be utilized concurrently to support the data warehouse. We will use a combination of:

- **On-line Data Storage** --- This is disk based storage primarily for storing frequently used data products and as caching space for currently referenced data that were stored on slower devices. Normally, data on on-line storage can be accessed within 10 to 20 ms upon receiving request.
- **Near-line Data Storage** --- This is CD or MO jukebox based storage primarily for storing frequently referenced data products that are too large to be stored in on-line data storage. Data on near-line storage can be accessed within few seconds upon receiving request.
- **Off-line Data Storage** --- This is tape based storage primarily for storing infrequently referenced data products and back up archive medium for the warehouse. Access to data on off-line storage will be much slower and may require operator intervention.

To achieve better performance, the storage subsystem may move product data around between on-line and near-line storage devices based on usage frequency and usage characteristics. This type of data movement will be done totally transparent to the operation of other components in the warehouse, e.g., the Catalog Database and Access Interfaces.

Currently, the planned storage capacity for the validation data warehouse includes about 200 GB of on-line data storage, 640 GB of near-line fast MO data storage, and 300 GB of slower CD-based data storage. Both the MO and CD jukebox will be equipped with writable drives allowing data to be recorded onto MO or CD for off-line storage.

5.3.5 Application and User Access Interfaces

The application and user access interfaces, shown in Figure 5.9, provide applications and users access to the data warehouse. This includes not only access to query and retrieve data products, but also access to setup and control data streams and agents, and to monitor and control the operation of the data warehouse.

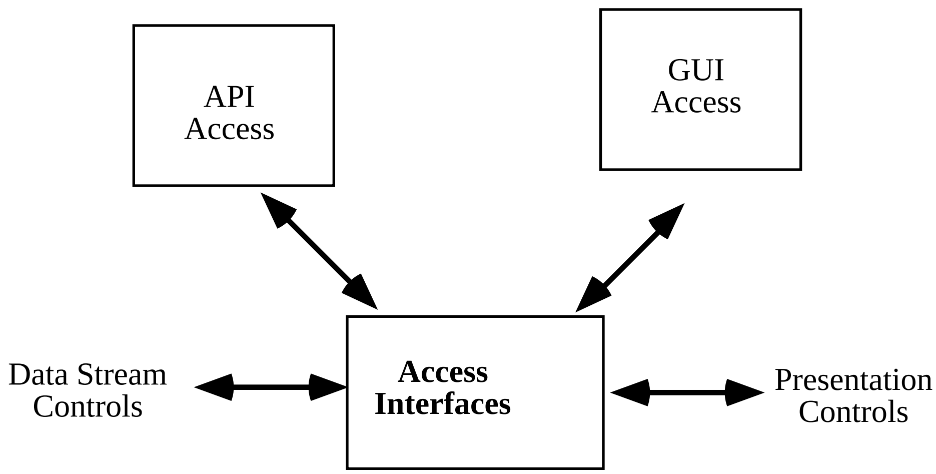


FIGURE 5.9. APPLICATION AND USER ACCESS INTERFACES

We will first implement a set of low-level common interface access functions. Once this layer is developed, two different high-level access interfaces will be developed for the data warehouse system:

- **Graphic User Interface (GUI) Access** --- This is a platform independent web-based interface allowing users to access the data warehouse using form-like graphic interface. In addition to HTML forms, client-side Java applets may be developed to enhance the user interaction support.

- **Application Program Interface (API) Access** --- This is a set of program language interface for accessing the data warehouse. Initially, we will only provide supports for RSI's IDL. Support for other programming languages may be added when it is possible.

The data warehouse will be implemented as a distributed system in which its components such as: the catalog data base, data agents, and the storage subsystem may be run on different computers. Because of this both the GUI and API access will be implemented utilizing a three-tier client-server model.

It will be a "**client-server**" system because user applications and GUI will most likely be run on a host different from where the catalog database is located. It will be a "**three-tier**" system because there will be a middle layer placed in between the client and the server. For example, in the API access, database access to RSI's IDL will be provided by Visigenic's Object Request Broker (ORB) which interfaces with database using the Open Database Connection (ODBC) protocol. In the GUI access, the web server will be the middle layer which translate users HTTP requests to database access.

5.3.6 Overview of the AIRS Validation Software Development

Functionality & Purpose

AIRS validation software functionality has been divided into two separate applications, one for performing "meso-scale" analyses over areas represented by multiple orbits and scan lines, and the other for "micro-scale" examinations of atmospheric conditions on a per footprint basis. Both approaches differ in regards to the type and amount of data required, and the analytical functions utilized.

Meso-scale, or orbit- and scan-based, validation analyses utilize various types of mapping functions to detect anomalous data values or atmospheric conditions by comparing parameters by time and location. Irregularly-distributed (or Level 2) point data, for example, can be transformed and reduced into a grid (Level 3), with each grid node representing a data value based upon surrounding Level 2 data values. The resulting Level 3 data can then be displayed and visually inspected for abnormalities. As another example, Level 2 data can be used in lag analysis, which attempts to correlate all points within a defined region; the resultant correlation can then be plotted and checked for peculiarities. To summarize, the purpose for performing these types of procedures is to be able to reduce potentially voluminous amounts of data covering relatively large geographic regions into smaller manageable quantities, which can then be visually and algorithmically analyzed for anomalous regions and other variabilities.

Once smaller regions-of-interest are identified, the data associated with these areas can be used as input to the micro-scale validation software. The extent of geographic coverage for the analysis tools implemented within this package is generally limited to footprint granularity or less. Validation processes at this level involve procedures such as atmospheric retrievals and comparisons and correlations of retrieved values with in-situ measurements and any other associated data sets. With these types of capabilities, any anomalous behavior or variability for any parameter can be traced back to source data sets that were used in the data generation process.

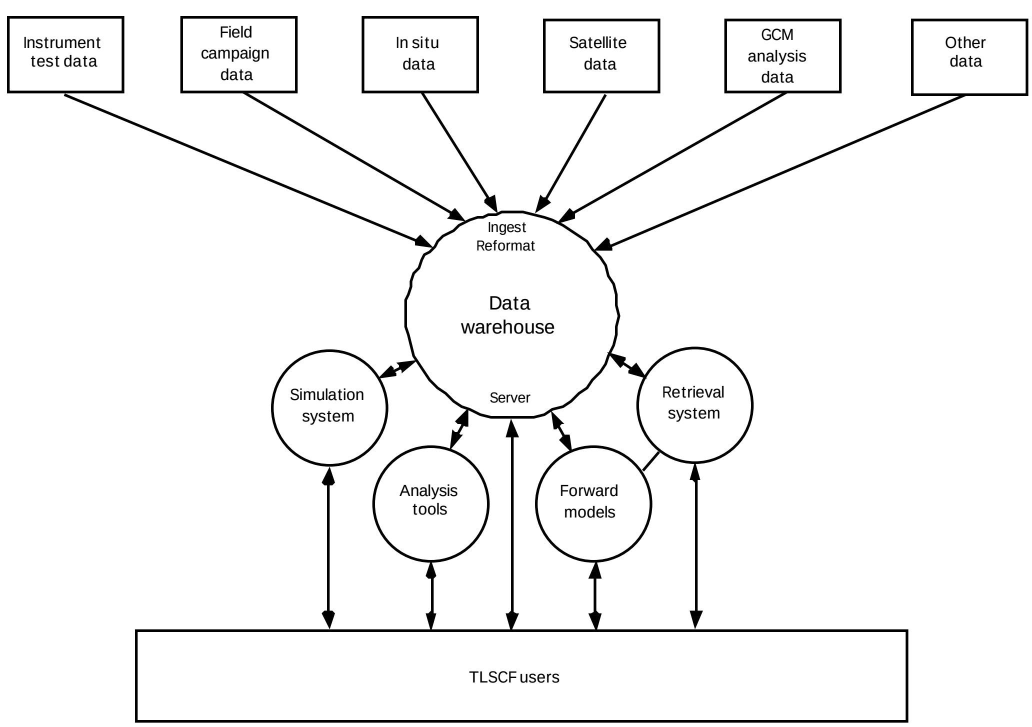


FIGURE 5.10 AIRS TLSCF VALIDATION SCHEMATIC

Architecture

The majority of software development for the AIRS validation effort will be under IDL 5.0, although there will be implementations of existing code written in C and FORTRAN. IDL 5.0 facilitates numerous desirable capabilities in the software development process including platform independency, streamlined user-interface development, and the ability to utilize an open-ended, easily-extensible, object-oriented code design paradigm. The choice to utilize IDL 5.0 also allows for algorithms and analysis modules developed in earlier incarnations of IDL to be easily integrated into the current development effort.

The AIRS validation process lends itself to the development of object-oriented software, as there are several “natural” hierarchies and groupings within AIRS and its connected data sets relating to data characteristics (coincident footprints, number of AIRS footprints per AMSU-A footprint, etc.) and types of analyses (lag analysis, etc.) to be performed.

Currently, there are two software packages under construction utilizing IDL 5.0. The first, tentatively labeled ASTAIRS (Analysis and Statistical Toolkit for AIRS) is designed for use as a statistics, analyses and visualization tool for validating AIRS Level 1 and Level 2 data sets at a sub-orbit granularity. The second, as yet untitled, is being developed primarily as a tool for the preparation (“pre-analyzing”) and subsequent processing of AIRS Level 2 and Level 3 data sets for the purpose of performing high-level validation and verification analyses on orbital, geographically large, areas-of-interest.

Implementation

Software development has already begun with the implementation of some of the mapping algorithms. The majority of the initial work, however, will be devoted to the design and utilization of the basic programming objects that are to be used as the basis for both of the applications-in-development. These objects will be based on natural groupings of the data: “footprint”, “retrieval”, “truth”, and “spectrum” objects, plus groupings of these objects themselves (“scanline” object, for example, would be a collection of “footprint” objects, “orbit” object would be a collection of “scanline” objects). In developing these entities, an emphasis will be placed on the definition of all objects required, rather than completely defining the methods and members of the objects themselves. Objects and their definitions will continue to be expanded as development progresses.

The next step in software development process will involve the process of establishing a link between an object and all of the data sets it may encompass. Part of this process will include the creation of a communication link between each of the IDL software packages and the WWW browser to the data warehouse. A standardized mechanism will need to be developed which allows data which has been retrieved from the data warehouse (through the use of the data browser) to be “passed” onto one of the IDL applications, either as an object or pointer.

Once data is able to be ingested into the data objects, the next step will involve the definition and implementation of the various validation analyses and functions as methods within the appropriate objects.

The final step in the initial software development process will be the instantiation of the developed objects within each of the IDL software packages. This will involve the creation of separate interfaces for manipulating the objects as required.

Specific Software

Quick Look:

1) Access, mapping and display of quick-look and diagnostic data
2) Make correlative GOES observations available.

Routine Validation Package (statistical in nature):

1) Times series of AIRS data at roughly 15 sites (e. g. Warm Pool).
2) DSD5 / radiosonde statistics.
3) Calibration coefficient analysis capability.

Routine Retrieval analysis Package (Statman)

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Appendix A: Definitions

The validation of AIRS data products is based on calculating quantities which characterize the usefulness of the measurements for meteorological operational and scientific analyses. Usefulness here means the ability to

- distinguish geophysical variability from measurement noise
- distinguish patterns or trends in the data from measurement artifacts
- estimate statistical parameters which facilitate use of the AIRS data in analysis systems

In determining this, we further need to

- estimate sampling errors and distinguish sampling errors from measurement errors
- separate correlative measurement errors from AIRS errors

The following definitions provide a foundation for undertaking these tasks.

A1.1 State Variable – The vector $\vec{x}$ of quantities characterizing the state or condition of the earth. As applied here, $\vec{x}$ characterized a localized region covered by one AMSU-A footprint, and extending from the surface up through the atmosphere. Continuous properties are decomposed into sums of basis functions multiplied by discrete state variable components x_i (svc). The true value of svc $\bar{x}_i$ is subscripted with τ, $\bar{x}_{i\,\tau}$, and correlative measurements are subscripted by c, $x_{i\,c}$.

A1.2 Ensemble – The sampling of states used to derive statistics. The statistical properties of the ensemble should equal those of the parent population being sampled. Here it will be sufficient that the sample first and second moments agree with those of the parent distribution. The population extends over time or may be instantaneous. Unless indicated as a function of t, populations extend over all observation times, and ensembles sample evenly in time. In the case of global or regional population, a valid ensemble equals an unbiased time and area weighted (A) weighted sample of the globe or region. The sample mean $\bar{x}_i$ and parent means $< x_i >$ are defined by

$$\bar{x}_i = \frac{1}{N_S}\sum_S x_i\,, \qquad < x_i >= \frac{1}{AT}\int_T\int_A x_i\; dA\,dt\,.$$

A1.3 Bias – the mean difference from truth,

$$b_i = \frac{1}{AT}\int_T\int_A \left(x_i - x_{i\tau}\right) dA\,dt$$

The instantaneous bias $b_i(t)$ excludes averaging over time.

$$b_i(t) = \frac{1}{A}\int_A \left(x_i - x_\tau\right) dA$$

A1.4 Stability – The power spectra of the bias with respect to time.

$$s_i(t) = \mathcal{F}\left(b_i^2(t')\right)$$

where $\mathcal{F}$ is the Fourier transform operator and t is the period of the spectral component. The drift is the change in instantaneous bias

$$d_i(t) = \frac{1}{T}\int_T \left[b_i(t+t') - b_i(t')\right] dt'$$

A1.5 Precision – The standard deviation of a ensemble of measurements taken at the same time and location and sampling the same state.

$$p_i^{\,2}(t) = \lim_{A \to 0} \frac{1}{A}\int_A \left(x(t)_i - < x_i(t) >\right)^2 dA$$

Precision is the random component of the errors occurring on the shortest time-scales over the shortest spatial scales.

A1.6 Accuracy – The root mean square (RMS) difference between measured and true values in excess of the precision and bias in the long correlation time/distance limit.

$$\varepsilon_i^{\,2} = \frac{1}{AT}\int_T\int_A \left(x_i - x_{i\tau}\right)^2 - p_i^2\, dA\, dt - b_i^2$$

Accuracy is the stationary, spatially homogeneous component of the systematic errors.

A1.7 Spatial Correlation – The correlation at position $(\vec{s}\,')$ with correlation length $(d\vec{s})$

$$\mathbf{C}_{ij}(\vec{s}, d\vec{s}\,') = \frac{1}{A\,T}\int_T\int_A \Big(\left(x_i(\vec{s} + d\vec{s}) - x_{i\,\tau}(\vec{s} + d\vec{s})\right)\left(x_j(\vec{s}) - x_{ij\tau}(\vec{s})\right) \Big) dA dt - \varepsilon_i \varepsilon_j$$

Spatial correlation is the spatially varying component of the systematic error.

A1.8 Spatial Resolution – The spacing between measurements, either the separation between grid points in the vertical are the separation between retrieved states in the horizontal. The AIRS unified retrieval algorithms retrieve one state per AMSU-A footprint. Each state is derived from 1 AMSU-A footprint and 9 HSB and AIRS footprints.

A1.9 Spatial Representation - The basis functions used to relate discrete variables to the continuous structure of the earth. The AIRS retrieval uses a uniform horizontal representation, except for cloud properties which are uniform over sub regions of the AMSU-A footprint.

A1.10 Horizontal Sampling – The averaging of the ensemble of states viewed for each retrieved state, and applies only to the horizontal. In the case of AIRS, the infrared radiances are sensitive only to cloud free regions of the view. For profile quantities, the horizontal sampling is height dependent becoming more uniform higher up where fewer cloud obscure the footprint. Coverage of the AMSU-A footprint by AIRS and HSB footprints depends on look direction and introduces spatially-correlated spatial sampling.

A1.11 Vertical Smoothing – The averaging of vertical atmospheric structure arising from the sensitivity of the measurement system to small scale structure.